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Self Heating Properties of Coal

Emil Braun

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

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Abstract

Three methodologies for predicting and controlling the likely occurrence of self-heating in underground coal mining environments were analyzed. No method was found to be completely satisfactory for general coal mine applications. One evaluation system was found to provide excellent guidelines for preplanning procedures prior to initiating full scale coal mine operations, but relied heavily on past mining experience and ventilation control. Another evaluation system used standard coal characterization parameters and geological conditions to predict the likelihood of self-heating, while the third system used a thermal test method and geological conditions as a predictor of self-heating potential. The self-heating properties of eight samples of western bituminous coal from four seams were determined by two different test methods - the Adiabatic Furnace and the Crossing Point Method. The data from the Adiabatic Furnace indicated that for most of the coals tested two reaction zones existed. The first temperature region extended from 25°C to about 85°C with activation energies varying from 32 kJ/mole to 55 kJ/mole, while the region above 85°C exhibited an activation energy ranging from 59 kJ/mole to 82 kJ/mole. Using the lower temperature region lumped pre-exponential and activation energy for each coal, critical heating rates are calculated for different strata temperatures. Based on those coals exhibiting self-heating in the field, critical heating rates in excess of 1.5°C/24 hrs at a strata temperature of 20°C can be expected to result in self-ignition of the coal. The Crossing Point Method yielded ignition temperatures ranging from 132°C to 154°C at an average heating rate of 0.58°C/min. An alternative plotting technique is described that suitably correlates Crossing Point Method data with end use experience. A brief review of pertinent literature is also presented to augment existing reviews and provide a clarification of the current understanding of those factors affecting oxidative heating of coal.

Keywords: Adiabatic furnace; coal; fire test methods; ignition temperature; self-heating; spontaneous combustion.

1. INTRODUCTION

The expansion of the United States coal mining industry into the western continental states poses technological and environmental problems that will have to be overcome to ensure the maximum extraction of coal under the safest conditions. The lack of experience in working the thick seams prevalent in these areas has raised questions regarding the self-heating characteristics of the coal. The mining of eastern United States coal seams has been ongoing for many years. Mining experience with these coal seams has defined the self-heating problem. Operators aware of these problems have attempted to take precautions to lower the probability of an ignition. Similar past experience is not available for directing the course of western coal mining.

At the request of the Department of Energy's (DOE) Office of Coal Mining, the Center for Fire Research at the National Bureau of Standards conducted a review to locate probable methodologies for predicting the likelihood of coal mining operations encountering self-heating problems in the course of coal extraction. Relevant methods were identified by reviewing the literature on self-heating of coal and by correspondence with other nations expected to have encountered similar problems. As part of this review, several coal samples were obtained for analysis and some attention was directed to more recent pertinent literature. The objective of this work was to identify and evaluate currently used test procedures to determine coal susceptibility to spontaneous combustion.

Mining authorities were identified in most western European countries and Japan. Requests for information on methods they employ to predict self-heating potential of coal resulted in responses from seven countries.

Country	Method
Canada	Under Development (CPM)
England	Past Experience (Research)
France	Past Experience
Germany	Design Specification (Ventilation Control)
Italy	No Method (Research)
Japan	Past Experience
Spain	No Method

These responses ranged from methods based on trial-and-error to methods based on material testing and classification. While England and Italy were continuing to conduct research in the understanding of self-heating in coal, their approach depends largely on the past experience of local mine operators. The Germans had the most elaborate system primarily based on past experience. Their system relies heavily on prescribing ventilation control strategies. The French and Japanese also rely on past mining experience, but they have not developed a formal system of evaluation. The Canadians have developed an evaluation system based on material testing, but appear not to have implemented it throughout the country.

Based on this information and a review of the literature, four approaches to predicting the likelihood of self-heating occurrences have been identified. These are :

1) The German System;

2) The Canadian System;

3) RASCAL System (this had previously been developed for DOE);

4) Adiabatic Furnace.

The evaluation procedures cited in this report attempt to predict the likelihood of self-heating occurrences based on a combination of geological, technological, and material parameters. The Canadian Liability Index [1] uses self-ignition temperature to characterize the coal sample, while RASCAL [2] and the German [3] procedures employ coal rank or type as the material characterization parameter. No evaluation scheme currently employs the data obtained from the adiabatic furnace as fundamental input for characterizing a coal mine's susceptibility to self-heating. However, work in the past [4,5,6] has shown that this method coupled with additional physical parameters holds some promise for a future evaluation system.

To assist in the evaluation of the Canadian system and the potential usefulness of the adiabatic furnace to form the bases for a new evaluation system, DOE provided NBS with eight coal samples taken from western coal fields. The self-heating characteristics of these samples were determined using these two test methods. The long term stability of these samples under moderately elevated temperatures was determined using an adiabatic furnace. The self-ignition temperature of these coal samples was measured by a ramped heating method known as the Crossing Point Method (CPM). This test method forms an integral part of the Canadian evaluation system.

During the past half-century, several extensive reviews of self-heating or spontaneous combustion research have been conducted. [2,7-11] It is not the intent here to repeat this procedure but to draw together some relevant information as it relates to the goal of predicting spontaneous combustion hazards. This report will first describe those factors currently identified as influencing a coal's susceptibility to self-heat. This will be followed by a review of the three established evaluation systems; the results of testing coal according to the CPM and adiabatic furnace method; and a discussion of the test results.

2. SELF-HEATING FACTORS

Research into the self-heating or spontaneous combustion of coal has been directed primarily towards developing an understanding of the oxidative mechanism controlling the low temperature combustion of coal. Kim [12] has stated that, generally, spontaneous combustion is a rank related phenomenon. As coal rank decreases, the hazard of self-heating increases. Therefore, factors other than "simple" oxidation must account for this rank dependence. While rank is a measure of coal fuel content, several physical properties that effect self-heating propensity also follow coal rank. For example, higher ranked coals rarely contain pyritic compounds or are soft which would lead to increased granulation. Researchers have long recognized that in addition to an oxidative mechanism, one must also understand how coal impurities (e.g. pyrites), moisture, and ambient temperature effect the rate of coal oxidation.

2.1 Oxidation

The primary mechanism of self-heating is due to coal interaction with oxygen and the subsequent inability of the coal to dissipate the heat generated in this reaction. This area has been reviewed by several authors. [7,13-18] In 1957, Coward [7] conducted an extensive review of research data on the spontaneous combustion of coal in the mining environment. He concluded that spontaneous combustion of coal can occur at normal mining temperatures due to the coal's slow oxidation by air. More recently, Yamasaki [19] conducted a study into coal oxidation that did not dramatically alter earlier conclusions. He found that the interaction of oxygen with coal was a surface phenomenon. The rate of oxygen consumption increased with increasing surface area per unit weight of coal and increasing temperature. As pointed out by Güney [14], in a mining environment, this reaction mechanism would continue to accelerate until ignition conditions were achieved unless adequate ventilation was provided to dissipate the excess thermal energy.

Carpenter and Giddings [20,21] divided the oxidation of coal into three stages. The various stages represent the ease with which coal can react with diffusional oxygen. The first stage controls the rate of oxygen consumption on the external and macropore surfaces, while stages two and three are controlled by the accessibility of oxidation sites in the micropore structure of coal. With the exception of one coal sample, they found that the activation energies for each stage were essentially constant, 67 kJ/mole, throughout the temperature range investigated - 75°C to 115°C. From mining considerations, these three stages are indistinguishable.

Sevenster [22,23], beginning at a temperature of 30°C, found that coal oxidation could be described by three temperature regimes. The calculated activation energies differed for each regime. The low temperature regime, 30°C to 50°C, and the high temperature regime, 70°C to 90°C, had higher activation energies than the middle 50°C to 70°C temperature range. In general, the activation energies for the high and low temperature regimes were similar, 14 to 40 kJ/mole and 19 to 42 kJ/mole, respectively. The activation energy for the middle regime was 8 to 19 kJ/mole. The value of the high temperature activation energy was probably due to chemical reactions of combustion, while the low temperature regime was controlled by oxygen adsorption. The middle regime was controlled by transport phenomena as described by Carpenter and Giddings. [20]

In analyzing research data on the kinetics of low temperature coal oxidation, Resnik and Chekhovskoi [24] found that two temperature regimes existed, each of which could be fitted by an Arrhenius equation. These yielded activation energies of 21 kJ/mole at 20°C to 70°C and 126 kJ/mole at 70°C to 90°C. These predicted values are somewhat higher than previously cited.

Because a critical heat balance exists during each stage of reaction, the existence of a reaction zone and its characteristic activation energy depend on the test apparatus. Differences in equipment design, sample size, sample granularity, and exposure time may explain the discrepancies cited above.

2.2 Moisture

The effects of atmospheric moisture on the self-heating tendency of coal have been demonstrated to be rank-dependent. While not directly addressing this question, Coward [7] does cite some data that show that the heat of wetting of dry coal is a decreasing function of increasing coal rank (table 1).

Hodges and Acheijer [25] and Bhattacharyya et al [26] showed that the presence of moisture in the atmosphere can accelerate the heat generation rate and, therefore, decrease the time to ignition by self-heating. Güney [27], using an adiabatic furnace, came to similar conclusions. These researchers found that when water vapor pressure in the air was greater than at the coal surface, moisture is adsorbed on the coal surface producing a heating effect. This self-heating increases the rate of oxidation leading to ignition. A cooling effect due to evaporation was induced if the water atmospheric vapor pressure was lower than the vapor pressure of the water in the coal.

More recently, work by Bhattacharyya [28] indicated that, for the coals tested, the rate determining factor was the adsorption of water vapor and that the rate of heat release during adsorption of water vapor was related to the hygroscopicity of coal. Mahajan and Walker [29] experimentally measured the heat of adsorption of water on coal and arrived at a value of 44.4 kJ/mole. This was comparable to the activation energy of dry coal, previously cited, in the temperature range of 50°C to 70°C and 70°C to 90°C. Their work also showed that the extent of adsorption depended on coal rank.

Panaseiko [30] investigated the ability of moisture to accelerate or retard the oxidation of coal. He found that the amount of oxygen adsorbed by coal decreased with increases in the amount of adsorbed water. More importantly, he found that the rate of oxidation had a maximum value over a narrow range of coal moisture content. The critical moisture content increased with decreasing coal rank.

Bacharach et al [2], in reviewing spontaneous combustion problems for American coal mines, asserted that the major environmental difference between the American and British mining conditions were the low ventilation humidities present in the western American coal fields. Therefore, coals mined in Britain that pose serious self-heating problems may be safely mined in the United States, although they may present certain difficulties in handling and storage once outside the mine environment.

2.3 Trace Species

The effects of trace species to induce or retard self-heating in coal has been studied for many years. Coward [7] presented data that showed that the presence of pyrites, while not necessary to induce self-heating, greatly increase the likelihood of developing self-heating conditions. Two mechanisms have been proposed to account for increased self-heating in coals containing pyrites. First, in the presence of moisture, pyrite oxidation increases the coal temperature which in turn increases the rate of coal oxidation. [2] Alternatively, the pyrite may swell and cause the coal to disintegrate increasing the rate of oxidation by increasing coal surface area . [12] Research has also shown that other trace species can effect self-heating propensity. Alkalies are known to act as accelerators, while borates and calcium chloride have exhibited retarding actions. [2]

2.4 Geological and Mining Conditions

Those geological features of a coal seam that increase the surface area exposed to oxygen will increase the coal's susceptibility to self-heating. Therefore, highly pitched seams, very thick seams, and seams with weak disturbed strata, faults or shallow overburden are the most vulnerable to self-heating. [5]

Mining techniques that increase oxygen accessibility to coal beds can also lead to a greater probability for self-heating. Also, the specific method of coal extraction can enhance unwanted air leakage into a gob or coal bed. Therefore, retreating long wall mining is preferable to advancing long wall mining because the air leakage paths do not occur across gob areas. [2,5] Ventilation conditions must be carefully controlled to minimize air leakage under all mining conditions. [3]

3. SYSTEMS FOR PREDICTING SELF-HEATING POTENTIAL

Traditionally, self-heating susceptibility of a coal field has been determined by experience. In newly developing fields this experience is lacking and coal extraction proceeds cautiously until sufficient data have been collected characterizing the coal field. This is a somewhat subjective process that could be proved wrong with changes in the geological conditions within the coal field as well as changes in the mining techniques. With a more structured understanding of the self-heating characteristics of a coal seam, extraction rates might be improved without unwittingly increasing the risk of self-heating occurrences.

Since many variables enter into a determination of self-heating susceptibility of a coal seam, several attempts have been made to develop systems that integrate the material, environmental, geological, and technological elements into an index of self-heating propensity. Changes in any parameter that can effect the probability of self-heating should be reflected by corresponding changes in the index. Using this index as a guide, optimum mining techniques, ventilation rates, detection systems, etc. can be implemented. Three such systems have been located and are reviewed. Two systems, the RASCAL System and the German System, consider coal rank as the determining material characteristic and place greater emphasis on mining and geological conditions. Only the Canadian System relies on a test method to measure coal self-heating propensity.

3.1 RASCAL System

The system known as RASCAL, Rapid Appraisal of Spontaneous Combustion Assessed Liability, was previously described and recommended for use in western United States coal fields by Bacharach et al. [2] It is summarized in Appendix A. RASCAL combines six factors that include coal characteristics and mining environment into an overall risk factor that is a measure of the potential risk of self-heating. The overall risk factor is divided into three categories: low risk (less than 10); medium risk (10-20); and high risk (greater than 20). Of the six factors considered, three define the nature of the coal, one defines the geological conditions, and two define the mining conditions.

Coal rank, as measured by oxygen content, the presence of pyrites, and hardness, which determines the extent of gob granulation, are measures of the oxidative potential of a coal bed. This system places the greatest emphasis on coal rank. This factor alone can place a coal bed in the medium risk category. Based on these three factors alone, a sub-bituminous coal seam, having a high oxygen content, will always have no better than a medium risk for developing self-heating problems.

Strata temperature is used by RASCAL to classify geological conditions. The hardness of the coal, roof pressure causing falls, faulting, and, as previously explained, pyrite concentration are among some of the factors that determine the surface area available for oxidation. As the rate of oxidation increases, thermal energy must be dissipated in order to prevent critical self-heating. Since the rate of oxidation and, thereby the rate of heat generation, is temperature dependent, elevated strata temperatures can produce an oxidation rate sufficiently high to prevent adequate cooling of the coal bed. According to RASCAL, strata temperatures in excess of 21°C can begin to have an accelerating effect on coal oxidation rates.

RASCAL describes mining conditions by two factors. The first is concerned with the transfer of moisture from the ventilating air stream to the coal bed. As the moisture content of the ventilating air stream increases the amount of heat liberated in to the coal bed during condensation of water can be sufficient to increase the oxidation rate above a critical value causing self-heating. Ventilating air stream moisture content in excess of 60% RH are considered to be significantly hazardous and will increase the susceptibility of a coal bed to spontaneous combustion. Unmined roof coal is the second factor used by RASCAL to describe mining conditions. The thicker the roof coal the more likely are occurrences of self-heating.

3.2 German System

Appendix B is a translation of a German Manual for Work Safety for the Prevention of Spontaneous Combustion Fires. [3] The document contains three sections plus an appendix. Section one is a general review of those factors affecting self-heating of coal. Sections two and three describe measures to be taken during the planning and operational phases of coal mining. In addition, the appendix contains a planning aid for the evaluation of the potential for self-heating. In general, this document relies on practical experience rather than a quantitative assessment of hazard to control decision making.

The planning aid is divided into two categories (figure 1). The first includes those parameters that cannot be controlled by the mining operation (i.e., geological, tectonic, petrographic) that effect self-heating potential of coal. The second are those parameters that are designed into the mining operation. They include fire protection measures and ventilation techniques. The weighting factors used in the example at the end of Appendix B sequentially increase down the form. However, since the weighting factors for each parameter are arbitrary, the document recommends that each site develop its own set of factors. This can only be accomplished through experience. This appears to be an iterative process where initial designs are implemented and, as mining conditions change, the design guidelines for a particular site are modified. The general utility of this approach as a predictive tool is, therefore, severely limited. It is interesting to note that the parameters cited in this document are considered critical by other evaluation systems and by researchers in the field of self-heating of coal.

3.3 Canadian System

The Canadian system [1] for evaluating the self-heating potential of a coal seam is composed of a Liability Index for coal and a Mine Environment Index. The product of these two indices yields a Risk Index for a given mine. A summary of this system can be found in Appendix C. Like the RASCAL system, the Risk Index places a mine into one of three risk categories; low (0-10), medium (10-20), high (20-40). The Liability Index relies on data from an ignitability test method that measures the relative ignition temperature of coal. This method is commonly called the Crossing Point Method (CPM) for determining coal ignitability [31] and it will be described in more detail later in this report.

The Mine Environment Index depends on a qualitative evaluation of the mining environment. This index considers coal loss, fissuration, and ventilation pressure differential as the variables controlling the potential for self-heating of a given coal seam. The Mine Environment Index ranges from 1 to 4.

The lower the index the less likely is an occurrence of self-heating. Worse case conditions are achieved when the three controlling variables are considered high. A low index indicates that these three variables are within normal limits and that the likelihood of self-heating is thereby controlled by the characteristics of the coal.

The CPM is used to determine the self-heating characteristics of a coal sample by determining the ignition temperature under ramped heating conditions. The relative ignition temperature is defined as the temperature at which the center temperature of a coal sample exceeds or crosses the external ambient temperature of the air in the furnace. The Liability Index is then defined as the ratio of average heating rate, °C/min, between 110°C to 220°C to the relative ignition temperature, °C. This ratio is arbitrarily multiplied by 1000. This index is used to classify a coal sample as to its self-heating potential. An index of 0 to 5 indicates a low probability for self-heating, while indices of 5 to 10 and greater than 10 represent medium and high, respectively, probabilities for self-heating. Eight coal samples were tested according to this method and the results will be discussed later in this report.

4. MATERIAL EVALUATION

The self-heating tendencies of eight coal samples taken from four western United States coal fields were determined using an adiabatic furnace and a rate of temperature rise apparatus, CPM. The adiabatic furnace provides a means for determining basic thermochemical parameters, while the CPM represents, in at least one evaluation system, a critical element in assessing self-heating potential.

For any given coal sample, the most important factors determining susceptibility to self-heating are the thermophysics and oxidation kinetics. The adiabatic furnace represents a method by which heat transfer from the sample can be reduced, thereby allowing for a clearer study of only the heat generating process within the sample itself. Environmental and technological factors would have to be combined with the results of the adiabatic furnace before a determination could be made of the likelihood of encountering self-heating problems in a given coal field. With regard to the CPM test, the Canadians have already attempted to construct an evaluation system.

4.1 Sample Preparation

The eight coal samples evaluated in this report are described in table 2. The source of the samples was established by DOE. They monitored the collection and shipment of the samples to NBS. The samples were drawn from eight different mining sites representing four different coal seams. Samples "A" and "C", from seam number B-2, represent the only samples taken from a mine with a known occurrence of self-heating induced fire. The fire was discovered in a sealed gob area.

Samples were prepared for testing by grinding and sieving in a glove box initially purged with nitrogen. Coal samples were separated into three ranges of grain sizes: less than 150 μm; between 150 μm and 180 μ; greater than 180

μm. Samples with grain sizes between 150 μ and 180 μm were used for testing. This ensured that test were conducted on granular material with little if any possibility for the presence of voids within the test sample. The interior of the glove box was cleaned between samples to minimize intersample contamination.

4.2 Adiabatic Furnace

4.2.1 Test Method

The adiabatic furnace used in this work and its basic operation have previously been described. [4,32] In general, an adiabatic apparatus is designed to minimize heat losses from a sample. This is accomplished by maintaining a sample and its environment at the same temperature. Operationally, once a sample has been brought to an elevated equilibrium temperature with its surroundings, the apparatus control system increases or decreases the temperature of the surrounding air and the sample surface in response to the thermal behavior of the center of the sample. Temperature-time data are recorded and analyzed to determine kinetic information about the test sample.

The analysis of self-heating data [4,33] has generally been done by assuming that the rate of chemical heat release follows the chemical reaction law of Arrhenius,

$$\dot{Q} = \Delta HV\rho A \exp(-E/RT) \qquad (1)$$

This is a first order law, where;

A = pre-exponential (min^{-2}),

E = Activation energy (kJ/mole),

T = Sample temperature (K),

ΔH= Heat of combustion (kJ/kg),

V = Volume of sample (m^3),

ρ = Density of sample (kg/m^3),

R = Gas constant (8.314×10^{-3} kJ/mole/K).

A heat balance on a coal sample yields,

$$\dot{q}_s = \dot{Q} - \dot{q}_L \qquad (2)$$

where the rate of energy storage in the sample, $\dot{q}_s$ (kW), is the rate of heat generation within the sample, $\dot{Q}$ (kW) minus the rate of heat loss from the surface of the sample, $\dot{q}_L$ (kW). The rate of energy storage in a sample is given by

$$\dot{q}_s = V\rho c \frac{dT}{dt} \qquad (3)$$

where;

c = heat capacity (kJ/kg/K).

During an adiabatic process, negligible heat is lost by the sample. Therefore, setting $\dot{q}_L$=0, combining equations (1), (2) and (3), and rearranging terms yields a relationship that describes the rate of temperature increase in the sample as a function of the heat generation rate.

$$\frac{dT}{dt} = \frac{A \Delta H}{c} e^{-E/RT} \qquad (4)$$

Since the adiabatic furnace is designed to minimize heat losses, equation (4) represents a suitable method for analyzing the data. The coals were tested in the adiabatic furnace after being ground and sieved in a dry nitrogen atmosphere, as previously described. A 76 mm high by 76 mm diameter cylinder made from a number 80 stainless steel mesh was filled with coal and placed in the furnace. Dry air flowed through the sample for the entire test. The effects of moisture on ignition delay time was not investigated in this study because it has been reasonably well documented in the studies previously cited.

4.2.2 Test Results

Figure 2 is the temperature-time data for the eight western United States coal samples collected by DOE. Initial furnace temperatures were between 50°C and 70°C. Samples "B", "C", and "D" all began at 50°C, while "H" had a starting temperature of 70°C. The remaining samples were tested beginning at approximately 60°C. Qualitatively, it can be seen from figure 2 that samples "B", "E", and "D" had the longest time delay to thermal runaway (i.e., spontaneous combustion). Since two coal samples were drawn from each seam, comparative observations are possible. For example, comparing samples "D" and "H" demonstrates, as previously observed [25,28,30], that initial sample temperature can have a dramatic effect on the time delay to thermal runaway. Sample "D" was tested at 50°C, while sample "H" was tested at 70°C. The 20°C difference in starting temperature translated into a 3.5 fold increase in delay time (40 hrs to 140 hrs).

By taking logarithms of both sides of equation (4), it is apparent that plotting the temperature-time data in figure 2 as the ln(dT/dt) versus 1/T the resultant line has a slope of -(E/R) and an intercept along the ln(dT/dt) axis at the ln(AΔH/c). The data were evaluated in this way by plotting the rate of temperature change, (dT/dt), as a function of the reciprocal of the temperature, (1/T), on semi-logarithmic paper. If our assumption of first order reaction is correct then the data should form a straight line with a negative slope. Least squares fitting of the experimental data would yield the activation energy, E, and a lump parameter pre-exponential factor combining A, ΔH, and c. The values for ΔH and c must be determined by another method.

Figure 3 shows the results of such a plot for the eight western United States coals. These plots indicate that the coals can be separated into two groups. Five of the coal samples ("A" through "E") show that at least two rate controlling processes are present. Samples "F", "G", and "H" show that a single rate parameter can be used to describe the their oxidative process. Since samples "H" and "D" were taken from the same coal seam, one would have expected to see comparable results. These two samples, however, were tested at different initial temperatures. While sample "D" was tested at 50°C and exhibited a two-stage reaction process, sample "H" reached initial equilibrium at 70°C. This was apparently too high a starting temperature to observe the first-stage reaction. Samples "F" and "G" also show no indication of the presence of multiple processes. These samples were taken from the same coal seam and, since the starting temperature for these two samples were comparable to the other low temperature tests 55°C and 60°C, they represent a distinctively different class of behavior.

Least squares fitting over the range of linear response yielded values for an apparent activation energy and lumped pre-exponential. These values and the temperature regimes over which they correspond are tabulated in table 3. For those samples that indicated a two step reaction, the activation energy varied from 32 kJ/mole to 55 kJ/mole with an average of 44 ± 9 kJ/mole for the first reaction mechanism and 58 kJ/mole to 82 kJ/mole with an average of 71 ± 10 kJ/mole for the second. Those samples with only one reaction mechanism had an apparent average activation energy of 77 ± 3 kJ/mole with a range of 74 kJ/mole to 79 kJ/mole. This was within the range of the second reaction mechanism of the two-stage results. The apparent activation energy for the second reaction mechanism appears to be consistent with other published values for bituminous coal. [5] Reznik and Chekhovskoi [24] have theoretically deduced the presence of two reaction zones for coal self-heating. They calculated that at approximately 70°C the oxidation mechanism radically changes with an increase in the activation energy. From table 3, it can be seen that the observed transition point between reaction mechanisms occurred within the range of 70°C to 90°C and that the activation energies increased. However, the measured values for activation energy computed based on these experiments differed by 50% from the predicted values of Reznik and Chekhovskoi. [24] According to their calculations, the first reaction zone should have an activation energy of 21 kJ/mole, while the activation energy in the second reaction zone was computed to be 126 kJ/mole. Heusinger and Münzner [34] experimentally determined the adiabatic self-heating characteristics of coal extracted from the Katharina, Prosper II seam and observed a two-step reaction. They found that the activation energy for the first reaction zone was 48 kJ/mole and 66 kJ/mole for the second reaction zone. In addition, the transition temperature between reaction zones occurred at approximately 84°C. These data appear to be consistent with our observations.

It was suggested [35] that the frequency factor determined in tests like the Adiabatic Furnace could be correlated to self-heating potential. From the data currently available, it is not possible to determine the value of the frequency factor. The pre-exponential occurring in equation (4) is a combination of several coal parameters. These are the heat capacity, heat of combustion, and frequency factor. These additional thermal and physical parameters have not been determined for the coal samples submitted for analysis. The use of handbook values for these parameters would result in a simple scaling of the pre-exponential values listed in table 3. Generally, any analytical method developed for predicting self-heating potential will require both the frequency factor and the activation energy. The pre-exponential for the first reaction zone ranged from 10^3 to 10^6, while the second reaction zone had values between 10^7 and 10^{10}.

Based on information supplied by DOE, samples "A" and "C" were taken from coal seams that had experienced self-heating problems. Ignoring for the moment environmental and technological effects associated with the particular coal mines, based on the work of Banerjee et al [35], one would therefore expect to see differences in either activation energy or pre-exponential between these coal samples and the other six samples. No obvious correlation appears to exist between propensity to self-heat and the activation energy or the pre-exponential factor. However, the use of actual thermal property data for each coal sample may result in a positive correlation between the frequency factor and susceptibility to self-heat. An alternative explanation for the lack of correlation between test data, as applied by Banerjee et al [35], and field experience may be due to the fact that all of these coal samples had similar thermal characteristics, but that technological, geological, and environmental factors varied significantly from mine to mine. With the information supplied by DOE, this possibility could not be assessed. However, there is no reason to suspect that either the activation energy or frequency factor alone is sufficient to correlate laboratory data to end-use hazard. These are only parameters that empirically describe a complex reaction mechanism. They, therefore, must be used together to determine the rate characteristics of coal. The use of these two parameters to provide a limited correlation will be discussed later.

4.3 Crossing Point Method

The Crossing Point Method (CPM) apparatus employed in this study was functionally similar to the CPM equipment previously described in the literature. [1,31] Basically, a CPM apparatus is a controlled furnace that linearly increases the temperature of the environmental air around a coal sample at a fixed rate. In the CPM system, heated air is passed over a prepared sample of coal. Recording equipment monitors both the temperature rise of the center of the sample and the surrounding air. The sample temperature lags the air temperature until the ignition temperature of the sample is approached. The rate of change in sample temperature begins to exceed the rate of change in the surrounding air temperature. The intersection of the center sample temperature and the surrounding air temperature is defined as the relative ignition temperature of a coal sample. This crossing point temperature is a function of sample thermal properties, mass of material, heating, and sample diffusion characteristics (i.e., uniformity of granulation and grain size).

4.3.1 Test Method

In previous furnace designs, pre-heated air was required to pass through a coal sample. [31] This resulted in an increase in the pressure across the upstream face of the coal sample. Pre-heated air was driven by this force through the sample circumventing the samples diffusional characteristics. This introduced an additional variable. Karn et al [36] has shown that flow through a coal bed is not only dependent on the pressure drop across the coal bed in the direction of gas flow, but also depends on the direction of fissure formation and granulation. In general, the actual flow through the coal bed differed among the coals they studied. Furthermore, once oxidation began, downstream coal was exposed to a reduced oxygen concentration. The system reported on here differs from those previously used by maintaining a more uniform oxygen fraction around the entire sample with a minimum pressure force applied to any sample face. This was accomplished by using low air flow rate, 500 cm^3/min, and a large furnace to sample volume ratio of about 110. Since the total air flow rate was not forced through the sample, the oxidation mechanism was primarily controlled by the diffusion of air. The diffusion of air through the sample, while not typical of coal mines, has been standardized by testing coal samples with grain sizes between 150 μm and 180 μm. In addition, downstream material was not necessarily exposed to vitiated air. Air vitiation, normal to the sample surface, was directed towards the sample center. The sample was a 76 mm high by 38 mm diameter cylinder, similar to the samples used in the adiabatic furnace tests. Figure 4 is a schematic drawing of the furnace and control/data acquisition system.

4.3.2 Test Results

Sample preparation was as previously described. Approximately 28 gm of ground coal was placed in the center of the furnace. The furnace was programmed to increase the air temperature flowing around the sample at a rate of 0.5°C/min. The actual rate was a little higher than this value and varied between runs from 0.53°C/min to 0.61°C/min with an average of 0.58°C/min. Typical runs of all eight coal samples are shown in figures 5 to 12.

The average heating rate and the relative ignition temperature for each coal sample are listed in table 4. The average heating rate was determined by a least squares fit of the furnace air temperature from approximately 90°C to 170°C. Relative ignition temperatures were defined as the crossover point of sample temperature and furnace air temperature. Because the heating rate and the sample mass did not greatly vary, direct comparisons of relative ignition temperatures were possible. Relative ignition temperatures were found to vary from 132°C to 154°C. Six of the eight samples tested had relative ignition temperatures that did not differ by more than 7°C (132°C to 139°C). Only two samples, "B" and "E", had higher relative ignition temperatures, 153°C and 154°C, respectively.

Based on ignition temperature alone, the CPM method does not appear to distinguish between those samples, "A" and "C", that were taken from coal seams that had experienced self-heating and those samples that have not reported self-heating occurrences. In order to normalize the data for differences due to heating rate, Feng et al [1] developed a figure of merit (table 4) to evaluate CPM data. These values are also used in determining a mine's liability to self-heating in the Canadian Evaluation System. The figure of merit is computed by

$$\text{Liability Index} = \frac{\text{Heating Rate}}{\text{Ignition Temperature}} \times 1000 \qquad (5)$$

The Liability Index values for these coal samples were all below 5. This indicates that these coal samples have an approximately equivalent, but low, potential for self-heating given identical geological and technological conditions.

5. DISCUSSION

To develop a reliable predictive system for the quantification of self-heating potential of a coal mine, several factors must be considered and combined into a working model. These include mining technique, geological characterization, and coal characterization. In order to maximize the rate of coal extraction and maintain, at a minimum, the likely occurrence of self-heating incidents, a mining technique must be designed consistent with the type of coal and geological characteristics found in a specific coal field. A good predictive system would allow for the evaluation of alternative extraction methods as they impact on self-heating.

The three systems reviewed in this report address each of the three parameters to a varying degree of detail. In total, the German system is the most comprehensive design tool controlling mining techniques to reduce the occurrence of self-heating, but it has no means to measure quantitatively coal susceptibility to self-heat. It requires that consideration be given to self-heating problems in the planning stage prior to actual full-scale production mining. However, because of the arbitrary weighting method used in the German system, the objective importance attributed to any one factor in the overall system is not clearly defined and relies heavily on past experience. This severly reduces the general utility and transportability of the German system to other coal fields that have limited use experience.

5.1 Mining Technique

Of the three parameters necessary for an evaluation system, mining technique, or the method used to extract the coal, is the only one that can be controlled. It is only indirectly addressed, if at all, by the RASCAL and Canadian systems. This oversight on the part of the Canadian system may be understandable, since it was intended for use in a specific coal field under presumably identical extraction conditions. The RASCAL system, however, is a general purpose evaluation system intended for use in western United States coal fields where several extraction methods can be employed. RASCAL does not consider the selection of an extraction method, sealing method, or ventilation method as a means to control the self-heating of coal, while the German system goes into great detail regarding the type of mining operation. Factors such as the direction of ventilation air movement with regard to extraction direction, the nature of the extraction method (e.g., advancing or retreating long wall, continous mining, etc.), the presence of coal pillars, and the type of sealing method are all addressed in the German system.

5.2 Geological Characterization

The geological components considered by the RASCAL system are nearly as detailed as in the German system, while the Canadian system combines many elements into four broad categories.

5.3 Coal Characterization

The elements included in the coal characterization parameter are also more detailed in the RASCAL and German systems than in the Canadian System. Although this may appear to be a shortcoming of the Canadian system, it may in fact be its virtue. The other systems rely on an analysis of the coal (i.e., coal rank, pyrite concentration, hardness, etc.) as an indirect measure of the coal's self-heating potential. The presence of other accelerating or inhibiting factors are ignored. By relying on a thermal test method for measuring a coal's susceptibility to self-heat, the Canadian system represents a more general measure of a coal's self-heating potential and is less susceptibile to oversight of critical parameters not considered in a limited physical characterization. The thermal test method used in this evaluation system is the CPM. It measures the relative ignition temperature of a coal sample when it is heated at a fixed rate. This provides the necessary information for the determination of a coal's liability index and distinguishes this evaluation system from the others.

5.4 Coal Evaluation

Eight coal samples were evaluated by two test methods: the adiabatic furnace and the CPM apparatus. While no evaluation system uses the data provided by the adiabatic furnace, the CPM apparatus is an integral part of the Canadian evaluation system. The data from the CPM apparatus is used to develop a Liability Index that is combined with other mining and geological conditions to arrive at a measure of coal susceptibility to self-heat.

5.4.1 Adiabatic Furnace

The data from the adiabatic furnace has traditionally been used to study fundamental kinetic properties of a broad range of materials. The data on the eight coal samples showed that coal has two reaction zones. One regime below 85°C had an activation energy between 32 kJ/mole and 55 kJ/mole. The second reaction above 85°C had an activation energy range of 58 kJ/mole to 82 kJ/mole. This was consistent with prevaling theories of coal oxidation; however, neither the activation energy nor the pre-exponential were able to distinguish between coals from sources with known and unreported occurrences of self-heating. Work by Enig et al [37] showed that the data from the adiabatic furnace could be used to calculate a critical size for self-heating thermal ignition of a slab, sphere, or cylinder of material.

$$B_s^2 = \frac{\gamma k R T^2}{AE} \; e^{(E/RT)} \qquad (6)$$

Where : B_s = radius or half thickness of critical size

γ = geometric parameter

It can be seen from equation (6) that one requires, in addition to the data obtained from the adiabatic furnace, the thermal conductivity, k, of the material. Obtaining the additional information and applying equation (6), would allow one to use B_s as a measure of self-heating potential. It is still necessary to determine appropriate ranges for B_s before an evaluation system can be developed based on data from the adiabatic furnace.

As an alternative to the use of B_s, it is possible to use equation (4) to compute heating rates at different strata temperatures for the eight coal samples tested in this study, table 5. Heating rate data can be combined with field experience to determine a critical heating rate above which self-heating can be expected to occur. Since samples "A" and "C" were reported to have been taken from coal seams with previous occurrances of self-heating, heating rates equal to or above their minimum at a given strata temperature would be an appropriate critical heating rate. At 20°C, heating rates above 1.5°C/24 hrs, table 5, could be expected to result in self-heating, while raising the strata temperature to 40°C increases the critical heating rate to 5.4°C/24 hrs.

5.4.2 Crossing Point Method

The use of the CPM based Liability Index on coals tested in this report indicated a lack of correlation between self-heating occurrence and relative ignition temperature. Noting that the rate at which a coal sample approached the furnace temperature differed between samples, an alternative method for analyzing CPM data can be developed. A measure of the rate of heat generation by the sample can be calculated by taking the difference between the rate of heating of the furnace and the sample core. Ideally, once the sample and furnace air are in dynamic equilibrium, sample thermal lag should prevent the sample from crossing the furnace temperature. In fact, samples of inert sand tested in the CPM apparatus showed that the difference between furnace temperature and sample temperature remained constant, only depending on sample diameter. Therefore, a sample heating rate in excess of the furnace heating rate is indicative of the ignition process. The difference between the instantaneous sample heating rate and the instantaneous air heating rate is plotted as a function of furnace air temperature in figure 13, for all eight samples. It is interesting to note that of the four samples that follow the same trajectory, two of these samples, "A" and "C", are from a coal seam with a previous history of self-heating incidents. Samples "D" and "H" have a somewhat shallower trajectory, while samples "B" and "E" appear to have a nearly flat profile with an anomalous drop in the differential heating rate as the ignition temperature was approached. This may be due to the volatile content of these two coal samples. They were the only medium volatile bituminous coals tested in this series. Because of the grouping of the data, samples "F" and "G" should have similar field performance to samples "A" and "C". A review of the mining operations between these two coal seams may explain the lack of self-heating problems associated with the former samples.

This alternative analysis based on the rate of change in the difference between furnace air temperature and sample core temperature showed a positive correlation to observed self-heating characteristics of the coal samples. Furthermore, this analysis method differentiated between coals of different rank. (Samples "B" and "E" were medium volatile coals, while the other samples were high volatile coals.) However, due to the limited test population, it is not possible to extrapolate the usefulness of this method of analysis to all coals. Nor is it possible to build an evaluation system based on this method without further work.

Based on the self-heating history of the eight coals investigated, both test methods appear capable of distinguishing coals with a high susceptibility to self-ignite. The CPM method has the advantage of speed (approximately one day per sample compared to 3-4 days per sample using the Adiabatic Furnace method) and provides for the development of a simple ranking of coals. However, the CPM method is conducted at high heating rates without regard for characteristic coal mining temperatures. While the performance of the Adiabatic Furnace method is more time consuming, the fundamental data obtained (i.e., activation energy and lumped pre-exponential) can be used to directly evaluate coal heating rates at any chosen mine operating temperature. Critical heating rates, however, are determined by comparison to coals of known susceptibility to self-ignite.

6. CONCLUSION

A review of three evaluation systems for the prediction and control of self-heating incidents in coal mines indicates that:

- the German system is the most comprehensive, but relies heavily on past experience;
- the German system provides detailed planning guidelines that may be adaptable to the development of other coal fields;
- the German system and RASCAL system lack a means for the thermal assessment of coal;
- the RASCAL system is the only system that includes atmospheric moisture as an evaluation element;
- the Canadian system includes a method for the thermal assessment of coal.

All three systems have not been tested against a common set of coal fields with known self-heating properties.

The adiabatic furnace appears to be a useful instrument upon which to base a thermal assessment system for determining the potential for coal to self-heat. To take full advantage of this data, additional measurements need to be made and incorporated into equations (4) and (6) before absolute estimates of the propensity of coal to self-heat can be calculated. However, because it provides fundamental kinetic information about low temperature thermal oxidation of coal, the data can be applied to other areas of coal manufacturing such as coal storage facilities and transportation methods as well as coal mining. Kinetic data indicate that the oxidation of coal undergoes two thermal regimes. One regime was below 85°C with an activation energy of approximately 32 kJ/mole to 55 kJ/mole. The thermal regime above 85°C had an approximate activation energy of 58 kJ/mole to 82 kJ/mole. Using the kinetic data associated with the low temperature thermal region and equation (4), the self-heating potential of coal at any chosen mine operating temperature can be determined.

The Crossing Point Method was used to test the eight samples at an average heating rate of 0.58°C/min. The relative ignition temperature varied from 132°C to 154°C. The Liability Index specified for the Canadian analysis was not sufficiently sensitive to discriminate among the tested coals. An alternative plotting method that suitably correlated CPM data to end-use experience was developed. While a positive correlation was achieved with the CPM apparatus, the data are not readily useful at characteristic mining temperature changes.

7. RECOMMENDATIONS

None of the three evaluation systems appear to be general enough to use in evaluating western United States coal fields for susceptibility to self-heating. An evaluation system needs to be developed that is based on the best features of each system reviewed in this report. The new evaluation system should incorporate a thermal assessment test, like CPM or the adiabatic furnace, to determine coal characteristics. These should be combined with geological and technological data more consistent with western United States coal fields.

The new system should be carefully monitored and updated as additional information is made available by the coal mining companies and basic researchers.

8. GLOSSARY

Gob: The space from which coal has been removed and broken waste or filling materials have been left or placed.

Overburden: A consolidated or unconsolidated material overlying a deposit of coal.

Mining Techniques:

- Advancing Long Wall: A method of coal removal that is accomplished while advancing in the direction of the coal seam. With each pass of the cutting machine across the face of the seam, mining is halted to advance the cutting machine.
- Continuous Mining: A method of coal extraction that is accomplished by a continuous process of driving a mining machine into the coal seam.
- Retreating Long Wall: Similar to advancing long wall except that the cutting machine is installed such that with each pass of the cutting machine the mining equipment is drawn towards the entrance to the seam.

Pillars: Unmined coal in the form of columns left in a mine to provide roof support and air pathways.

Pyrite: Any of various metallic sulfides found in underground mining. A common sulfide found in underground coal mines consists of iron disulfide, FeS_2.

Rank: A measure of a coals volatile, carbon, or calorific content.

Seam: A stratum or layer of coal representing the coal bed.

Slope: An inclined entry in a dipping coal bed or an inclined tunnel to a coal bed.

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Table 1. Heat of Wetting of Dried Coal from Experiments by Porter and Ralston [7]

Coal	J/gm Dry Coal
Brown lignite (North Dakota)	107
Sub-bituminous (Wyoming)	80
Bituminous (Illinois)	29

Table 2. Description of Bituminous Coal Samples Used in Adiabatic and Crossing Point Method Furnace Tests

Sample ID	Mine Name	Seam Number	Ventilation Area	Coal Rank[a]
A	Somerset Mine	B-2	3 Dip 9 West	Hi Vol B[b]
C	Somerset Mine	B-2	Main Ext 5 West	Hi Vol B
B	L.S. Wood #3	Coal Basin	Slope	Med Vol[c]
E	L.S. Wood #3	Coal Basin	301 Wall	Med Vol
D	Sunnyside Mine #1	Lower Sunnyside	17 LT. Lw.	Hi Vol B
H	Sunnyside Mine #1	Lower Sunnyside (upper split)	19 LT. Tailgate	Hi Vol B
F	Hawksnest Mine	E	7-½ West	Hi Vol B
G	Hawksnest Mine	E	9 West	Hi Vol B

a) Classification of Coals By Rank - ASTM D-388
b) High Volatile B Bituminous Coal
c) Medium Volatile Bituminous Coal

Table 3. Summary of Adiabatic Furnace Data from Eight Western U.S. Coals

Sample ID	Initial Temperature (°C)	Temperature Range (°C)	Lumped Pre-Exponential (°C/min)	Activation Energy (kJ/mole)
A	60	60- 90	3.9×10^5	48 ± 11
		90-130	4.5×10^9	76 ± 7
C	50	50- 70	1.3×10^3	32 ± 9
		70-120	9.2×10^6	58 ± 10
B	50	50- 80	1.1×10^4	40 ± 7
		80-130	2.2×10^7	64 ± 9
E	60	60- 80	5.1×10^4	47 ± 5
		80-130	1.2×10^9	74 ± 9
D	50	60- 70	1.2×10^6	55 ± 7
		70-130	1.4×10^{10}	83 ± 9
H	70	70-130	8.9×10^9	79 ± 10
F	60	60-130	3.8×10^9	77 ± 9
G	55	55-130	2.1×10^9	74 ± 12

Table 4. Summary of Relative Ignition Temperature Data for the Crossing Point Method

Sample ID	Ignition Temperature (°C)	Heating Rate (°C/min)	Liability Index (min^{-1})
A	135	0.59	4.4
C	132	0.58	4.4
B	153	0.53	3.5
E	154	0.56	3.6
D	133	0.60	4.5
H	138	0.57	4.1
F	139	0.58	4.2
G	133	0.61	4.6

Table 5

Calculated Heating Rates for Eight U.S. Western Coals at Four Different Strata Temperatures Based on Equation (4)

Sample ID	Heating Rate (°C/24 hrs) Strata Temperature (°C) 10	20	30	40
A	0.8	1.5	3.0	5.4
C	2.3	3.7	5.7	8.6
B	0.6	1.2	2.1	3.4
E	0.2	0.3	0.6	1.1
D	0.1	0.3	0.6	1.1
H	<0.1	0.1	0.3	0.8
F	<0.1	0.1	0.3	0.8
G	0.1	0.2	0.5	1.3

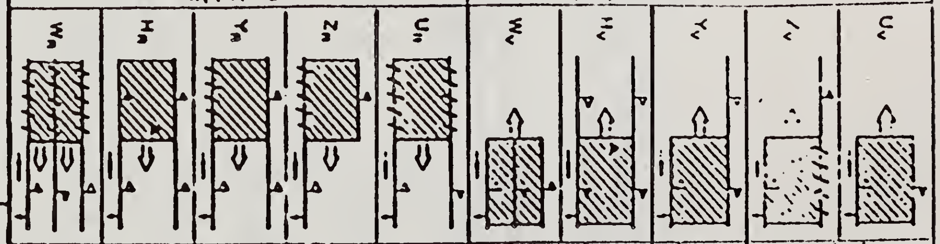
Figure 1 Planning Guide taken from German Evaluation System.

Calculation:
1. Weighing the criteria according to existing conditions
2. Multiplying importance and evaluation
3. Entering the factor W x B into selected design alternative
4. Summarizing factors W x B
5. Evaluating design alternative

Legend
⇒ Mining Dir.
— Hauling Dir
T Dips
▷ Fresh Air
▶ Exhaust Air

Criteria	Weight (W)	Evaluation (B) 0	1 – 2	3 – 4	5 – 6	7 – 10
Type of Coal			Anthracite/ Forge Coal	Gas Coke open burning	Bituminous	
Dips			$0-40^g$	$40-60^g$		$60-100^g$
Lode thickness			< 1.40 m	1.40 - 2.00 m	2.00 m - 3.00 m	> 3.00 m
Pyrite contents		NONE	OCCASIONAL		REGULAR	HIGH
Disturbances/ Area Tectonics		NONE	MINOR		MEDIUM	HIGH
Parallel lode in Roof/Top Coal		NONE	LITTLE		MEDIUM	HIGH
Coal Islands Residual Pillars		NONE	DAMMED UP TREATED OR SEALED			CRUSHED, FREELY EXPOSED, UNTREATED
Sealing measures		NOT NEEDED	Hydr. Setting material	OTHER material Dust barrier etc.		needed, but not performed
Securing Approaching & Trailing Edges		NOT NEEDED	Hydr. Setting material	Other material Dust barrier, etc.		Needed, but not performed
Slow Air Currents		NONE	unimportant currents			Important currents

DIRECTION OF MINING OPERATION



RETREATING W_R B	W_R W x B	H_R B	H_R W x B	Y_R B	Y_R W x B	Z_R B	Z_R W x B	U_R B	U_R W x B	ADVANCING W_V B	W_V W x B	H_V B	H_V W x B	Y_V B	Y_V W x B	Z_V B	Z_V W x B	U_V B	U_V W x B

Location of Operation:	Measures:	ΣW x B
Lod:	Securing approaching edges:	
Height:	Parrallel dams to miningwalls:	
Department:	Treatment of Residual Pillars:	
Sole:	Reduction of slow air currents:	
Direction of Mining:	Type of Ventilation:	

Evaluation: Sums from 0 – 50 : Little danger of Spontaneous Combustion
50 – 100 : beginning " " " "
100 - 200 : medium " " " "
200 - 300 : great " " " "

Remarks:

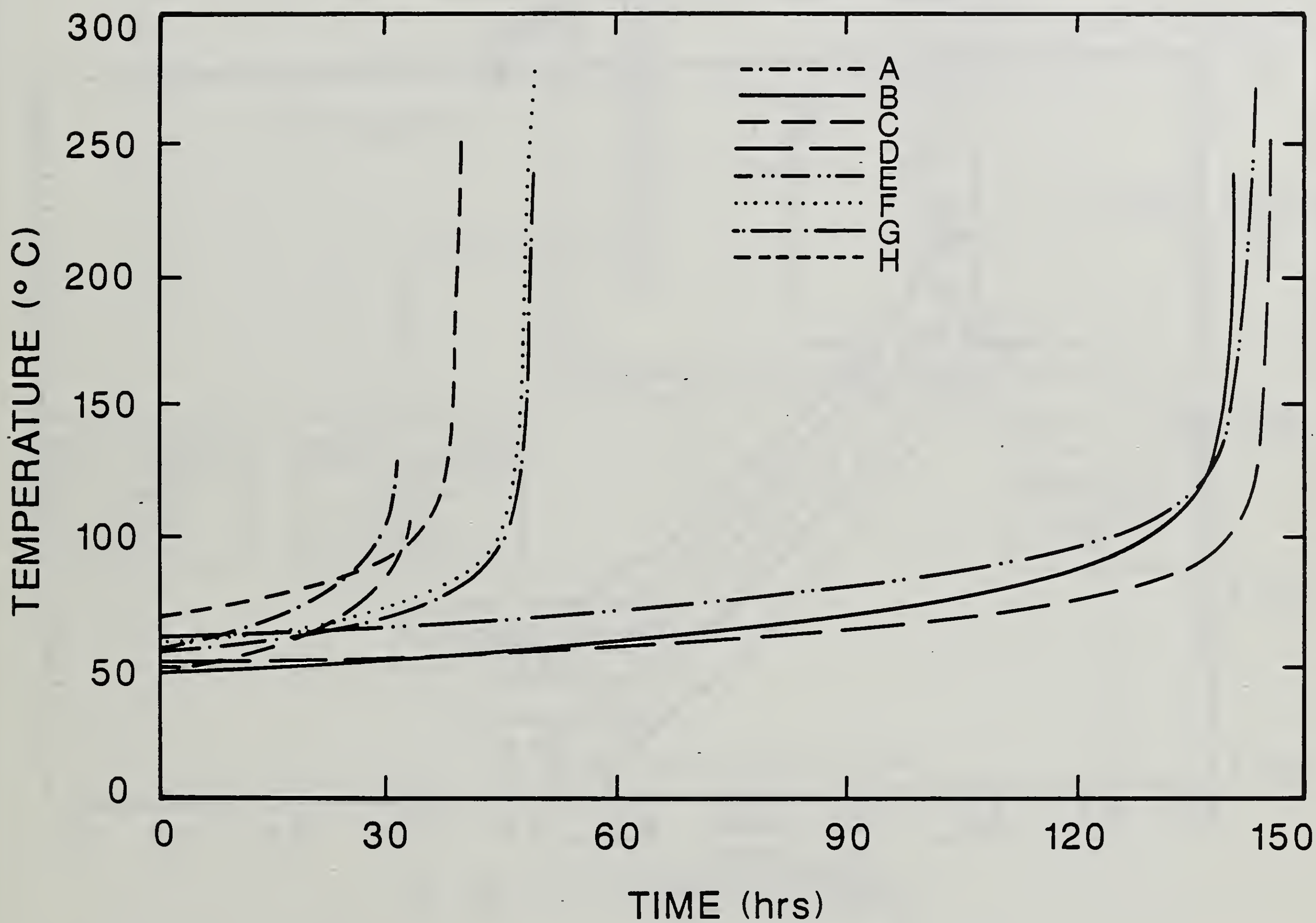


Figure 2 Temperature-Time curves for eight DOE coal samples taken from western U.S. coal fields tested in the Adiabatic Furnace.

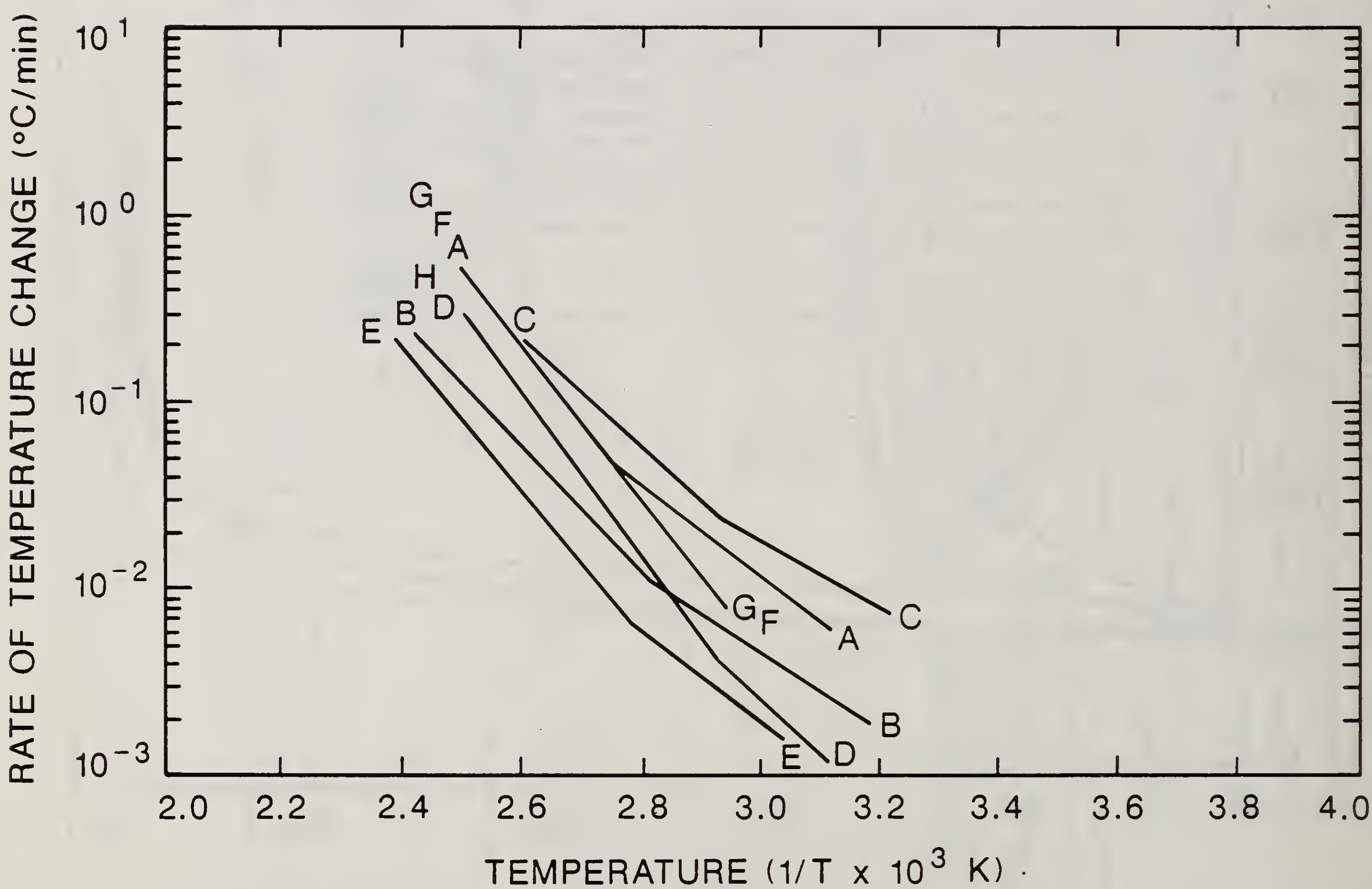


Figure 3 Semi-Log plot of the rate of temperature change versus 1/T (K^{-1}) for eight samples of U.S. western coals tested in dry air.

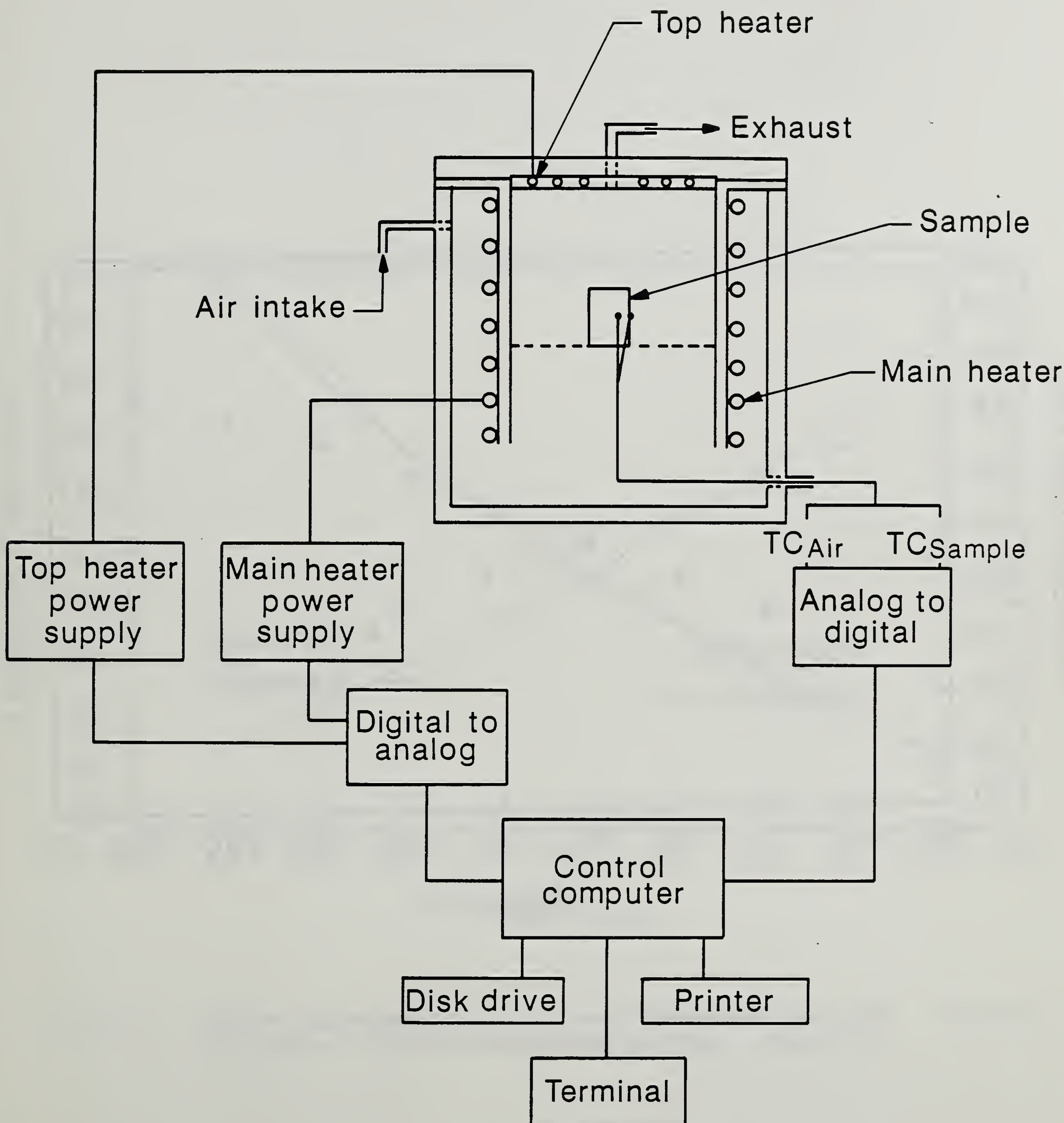


Figure 4 Schematic drawing of the apparatus used in the Crossing Point Method (CPM).

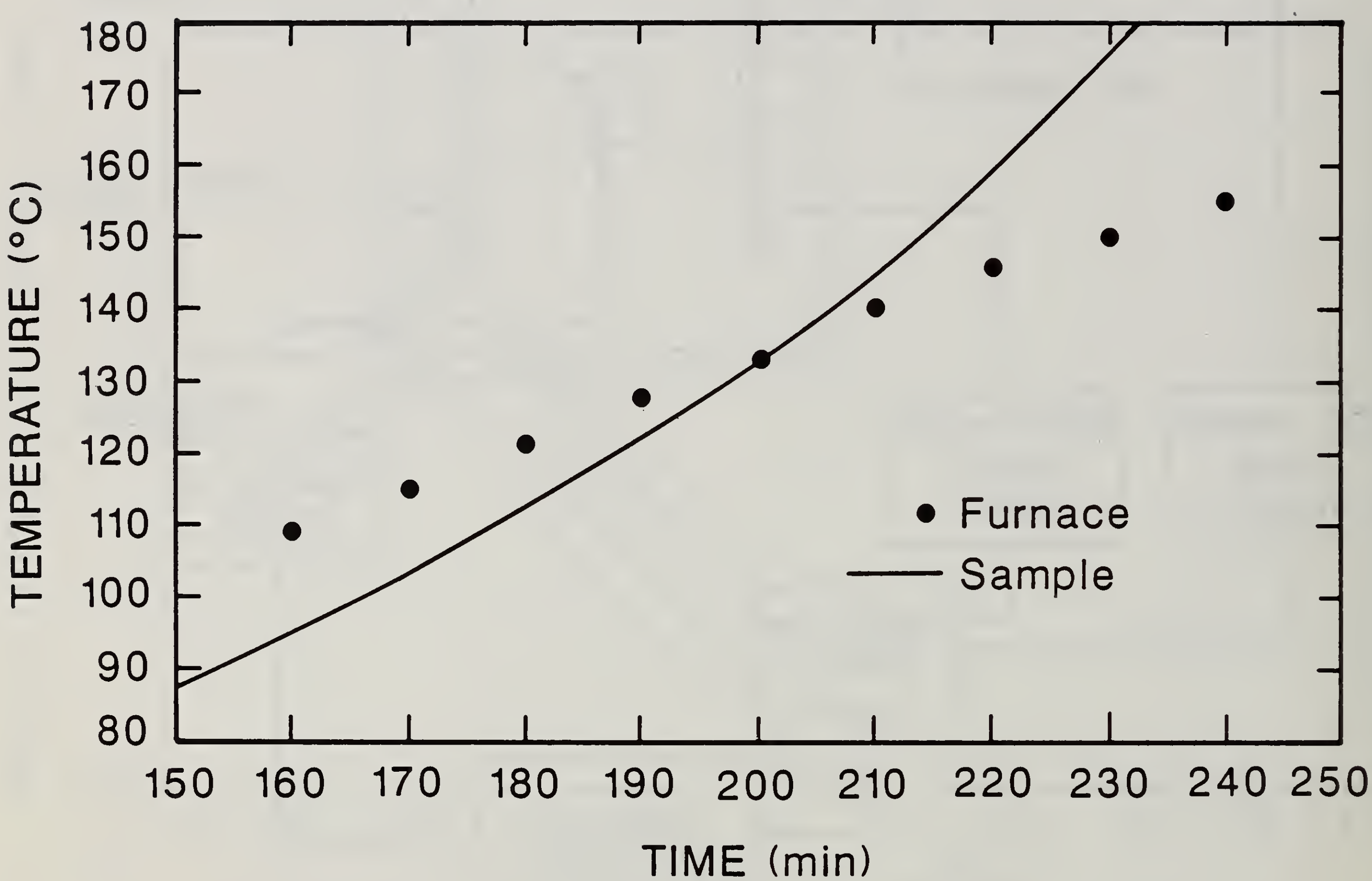


Figure 5 CPM test results for coal sample "A" heated at 0.59°C/min. Ignition occurred at 135°C.

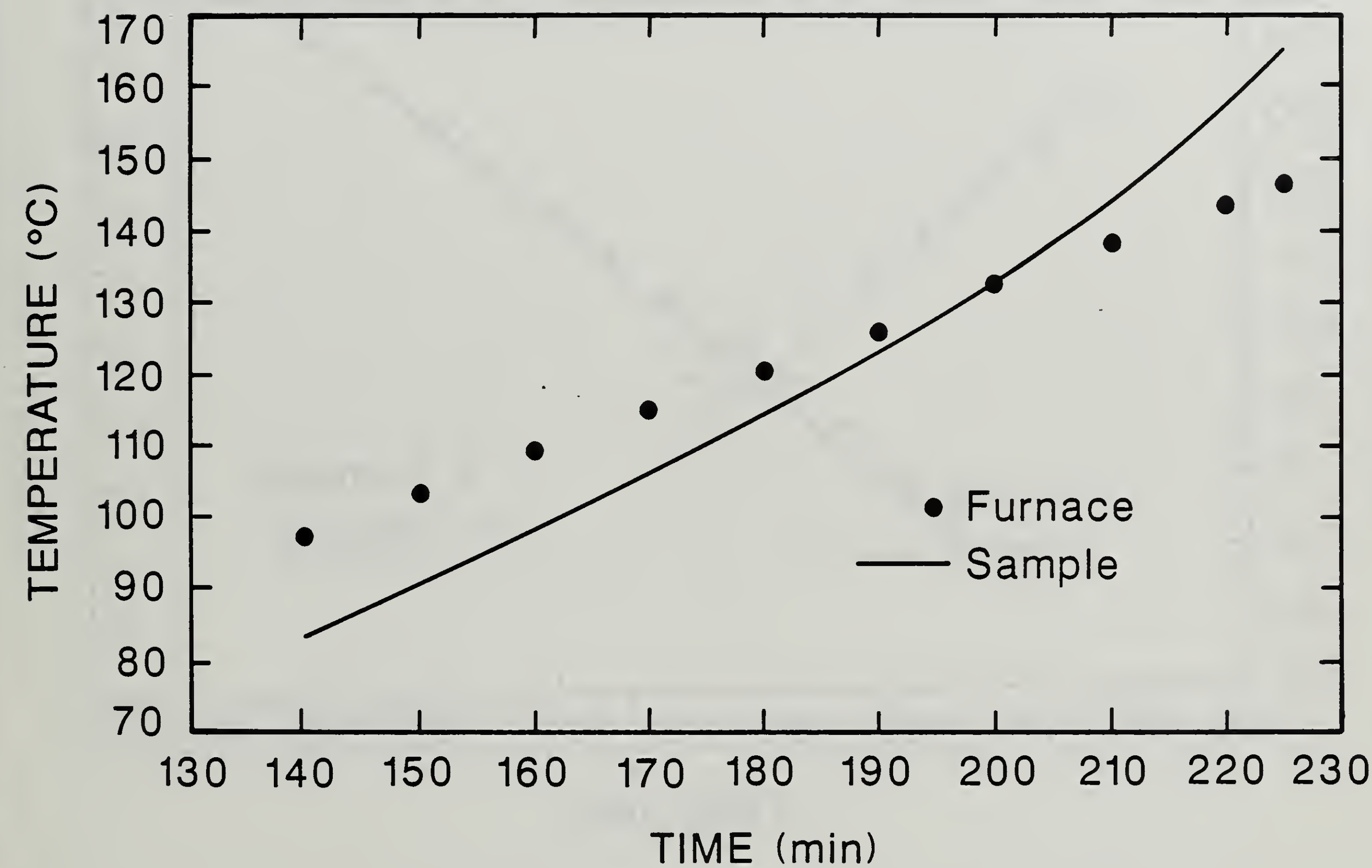


Figure 6 CPM test results for coal sample "C" heated at 0.58°C/min. Ignition occurred at 132°C.

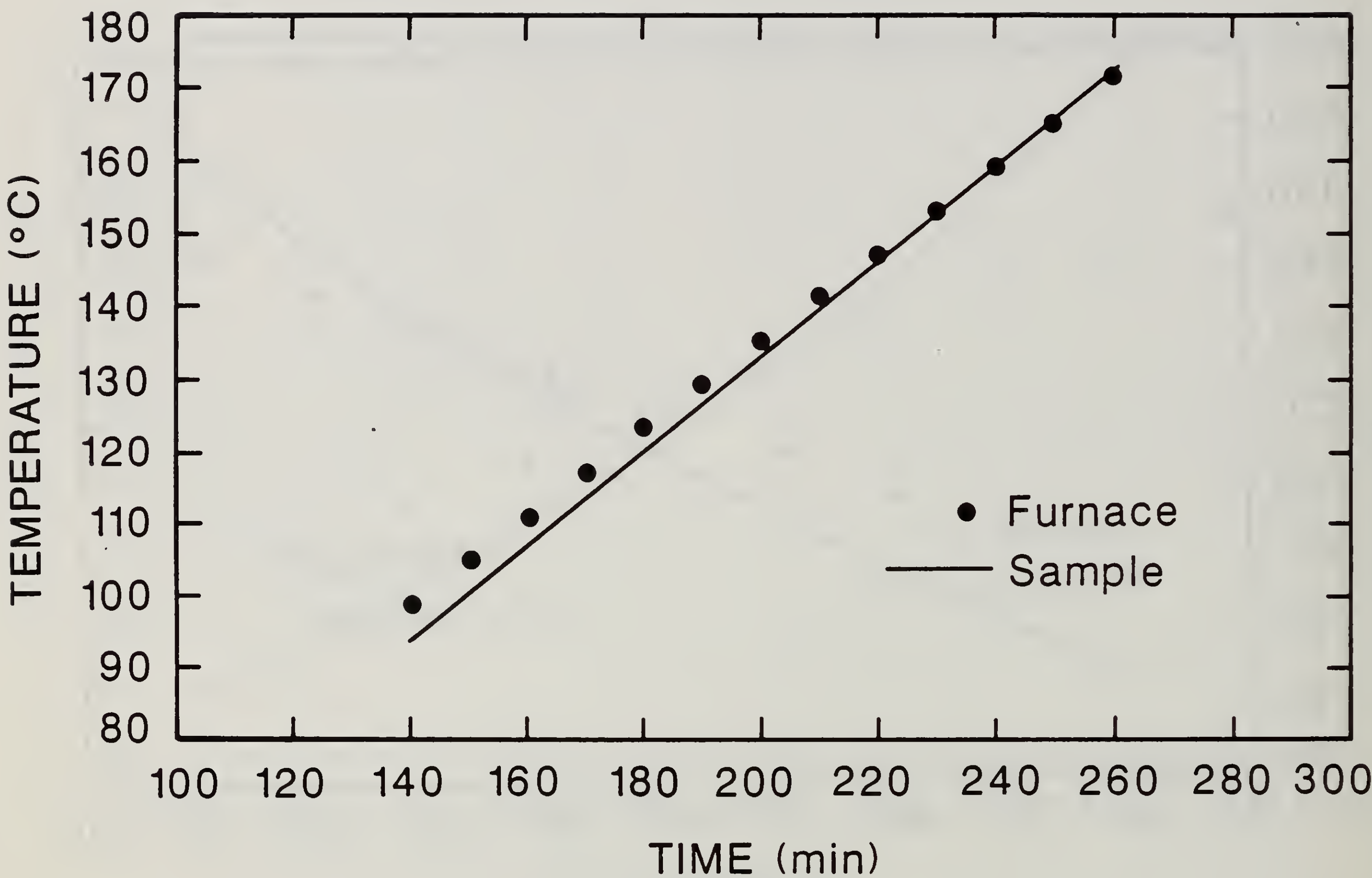


Figure 7 CPM test results for coal sample "B" heated at 0.53°C/min. Ignition occurred at 153°C.

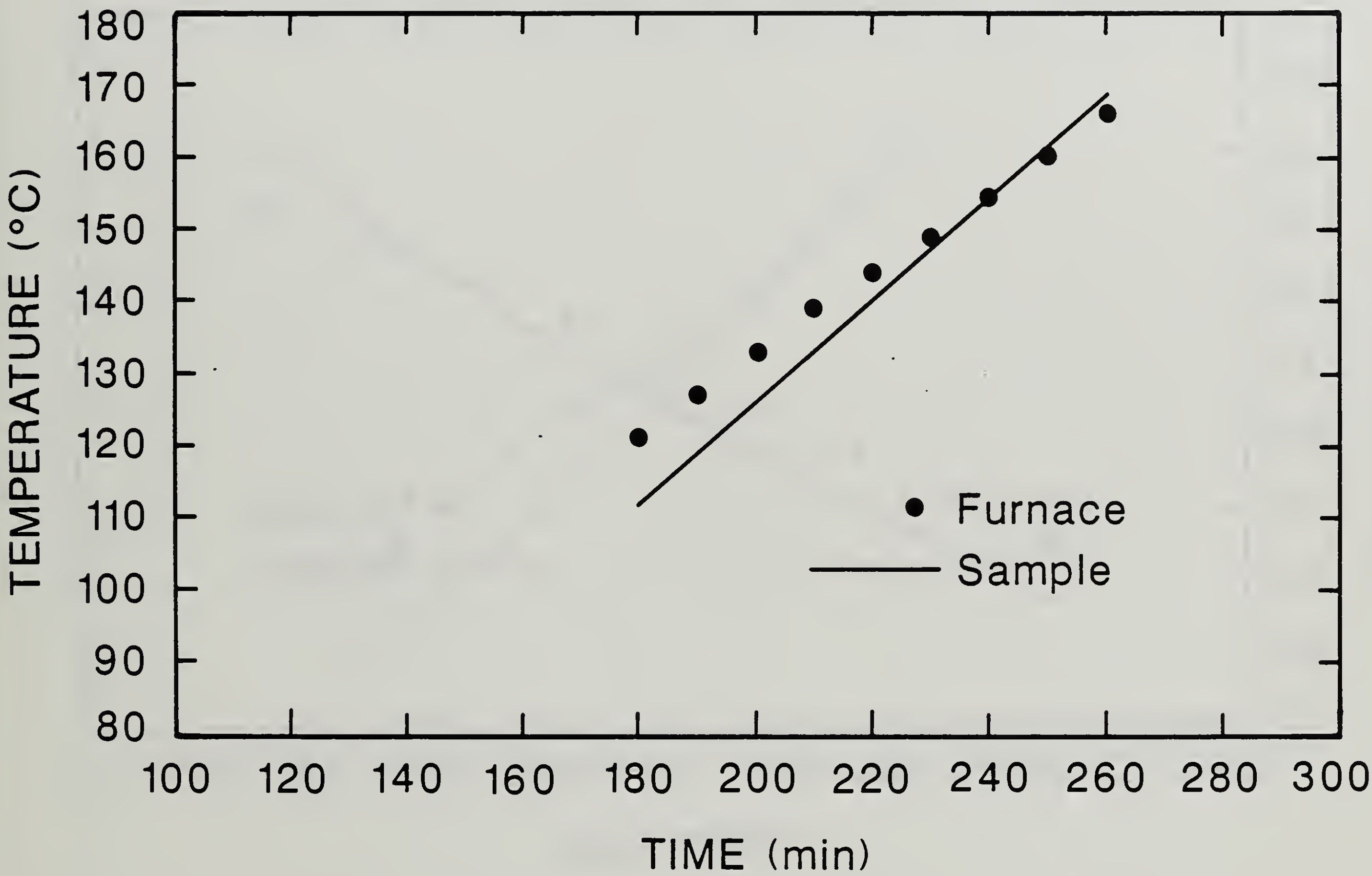


Figure 8 CPM test results for coal sample "E" heated at 0.56°C/min. Ignition occurred at 154°C.

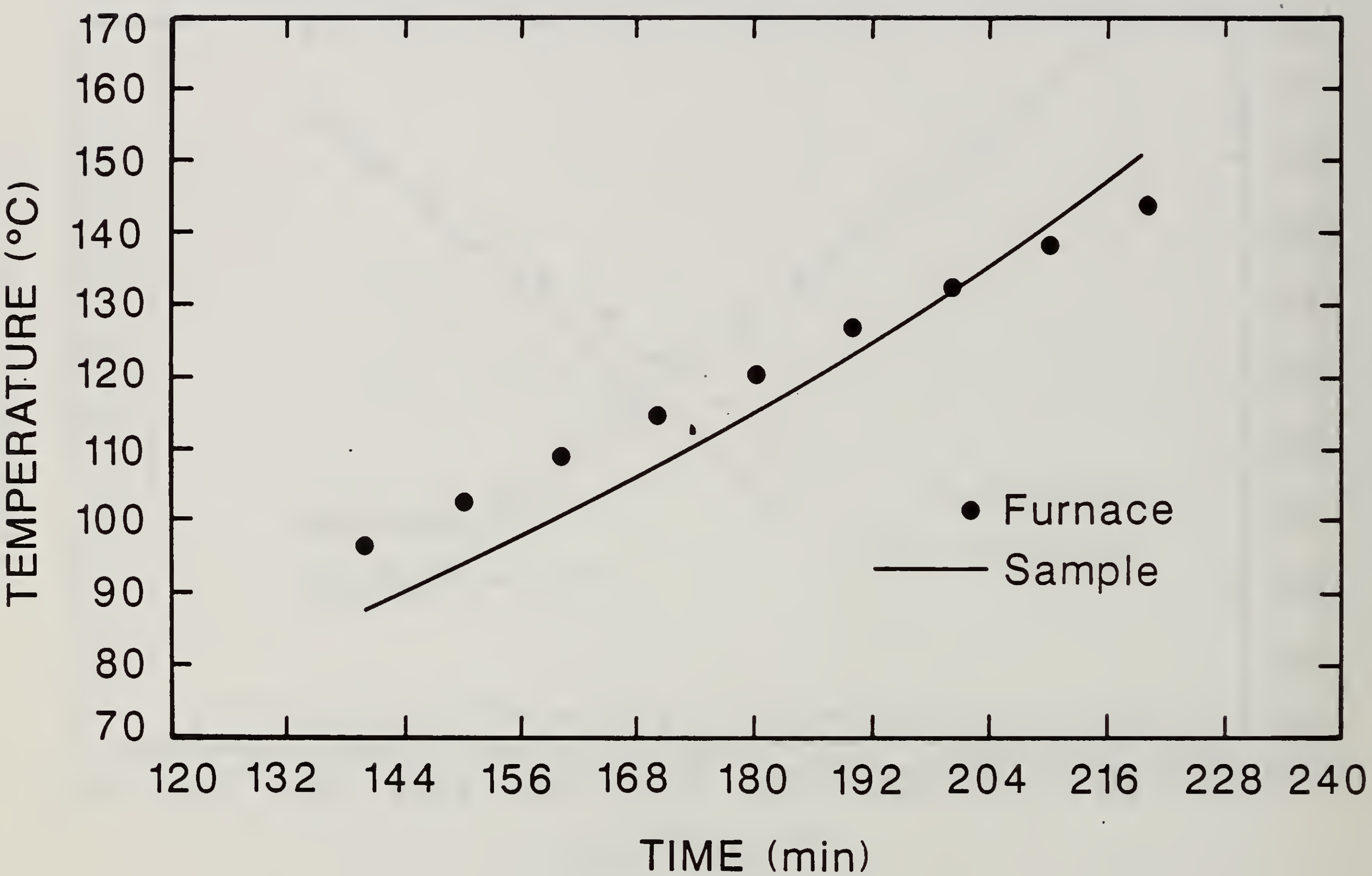


Figure 9 CPM test results for coal sample "D" heated at 0.60°C/min. Ignition occurred at 133°C.

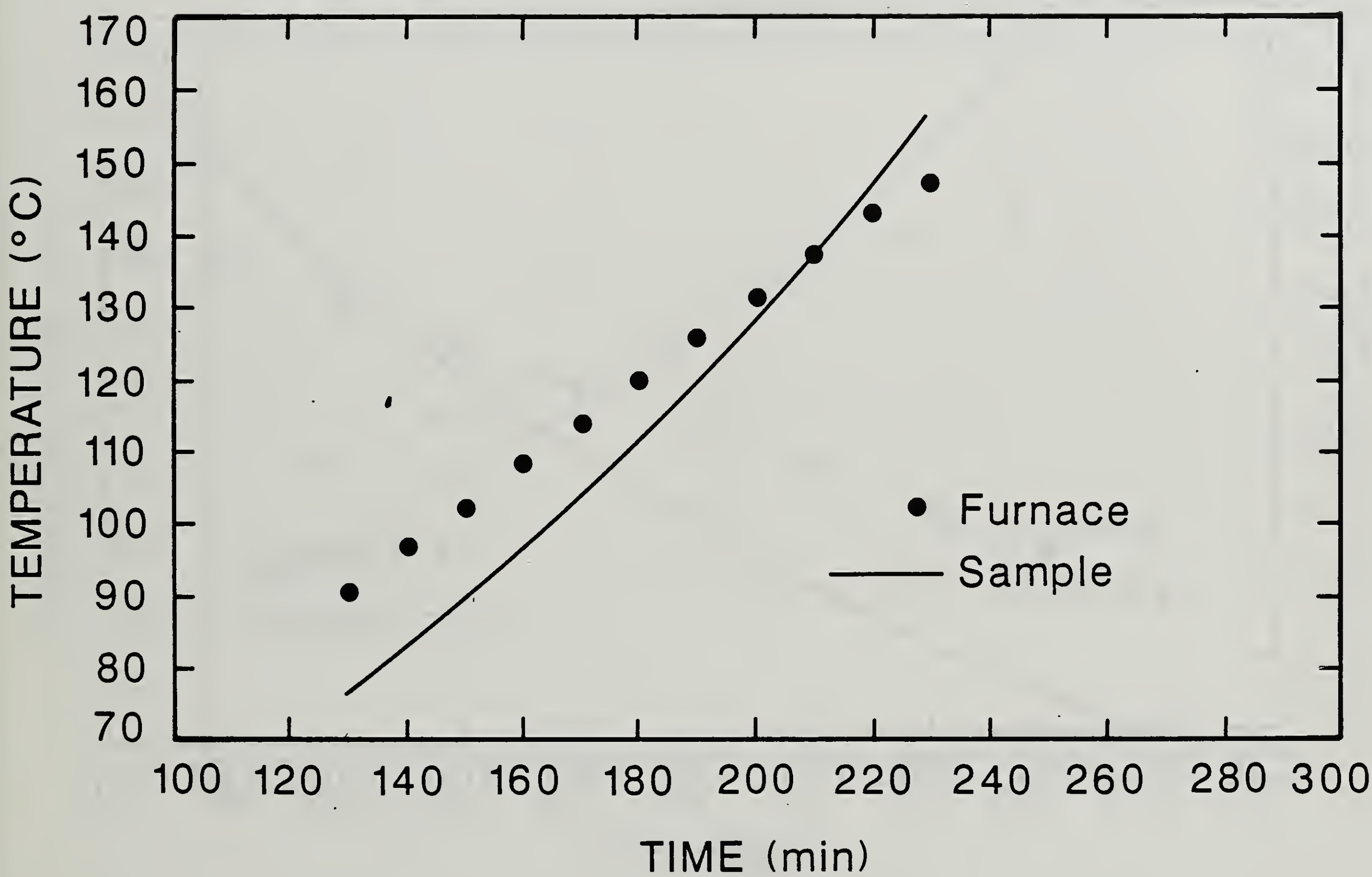


Figure 10 CPM test results for coal sample "H" heated at 0.57°C/min. Ignition occurred at 138°C.

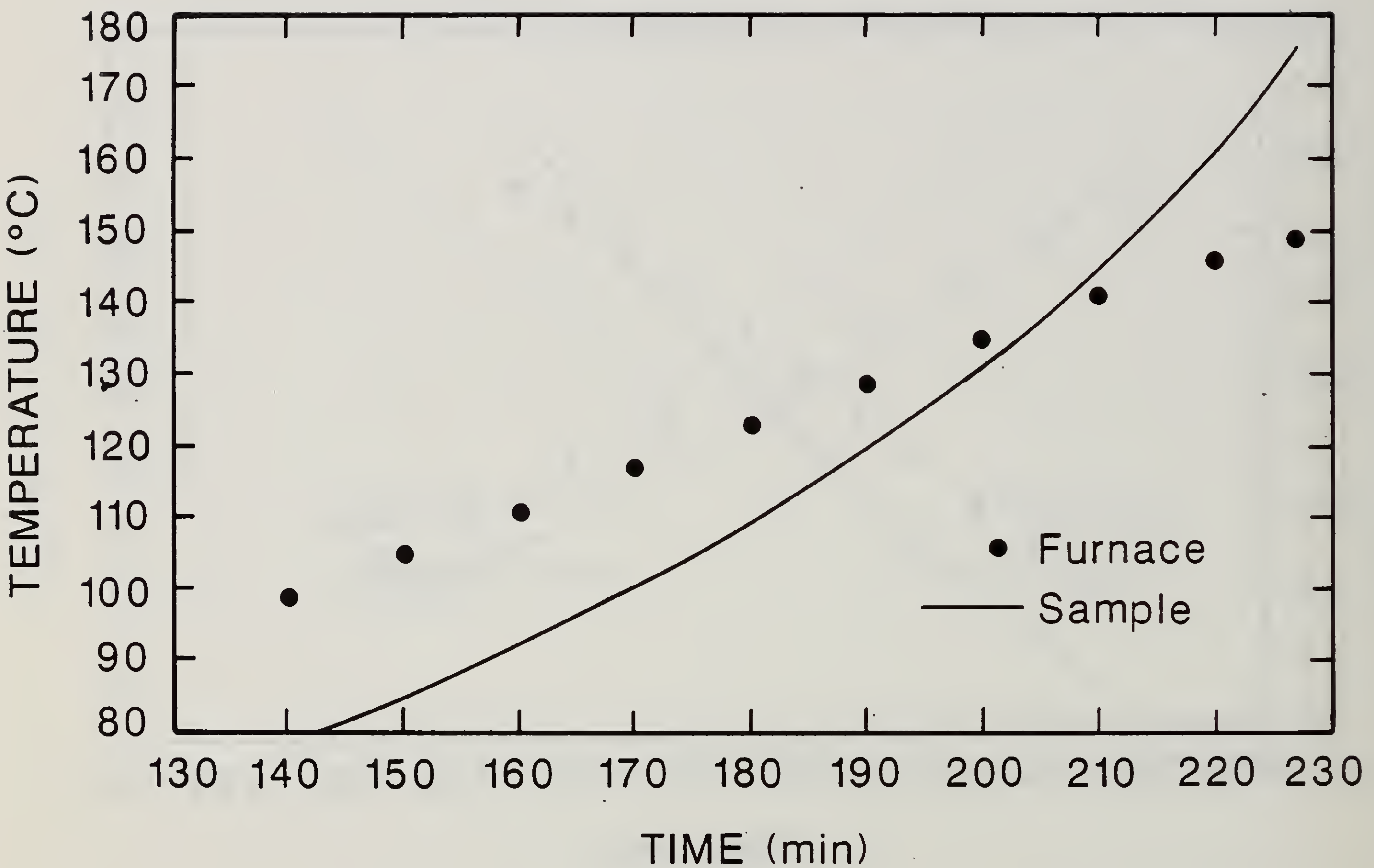


Figure 11 CPM test results for coal sample "F" heated at 0.58°C/min. Ignition occurred at 139°C.

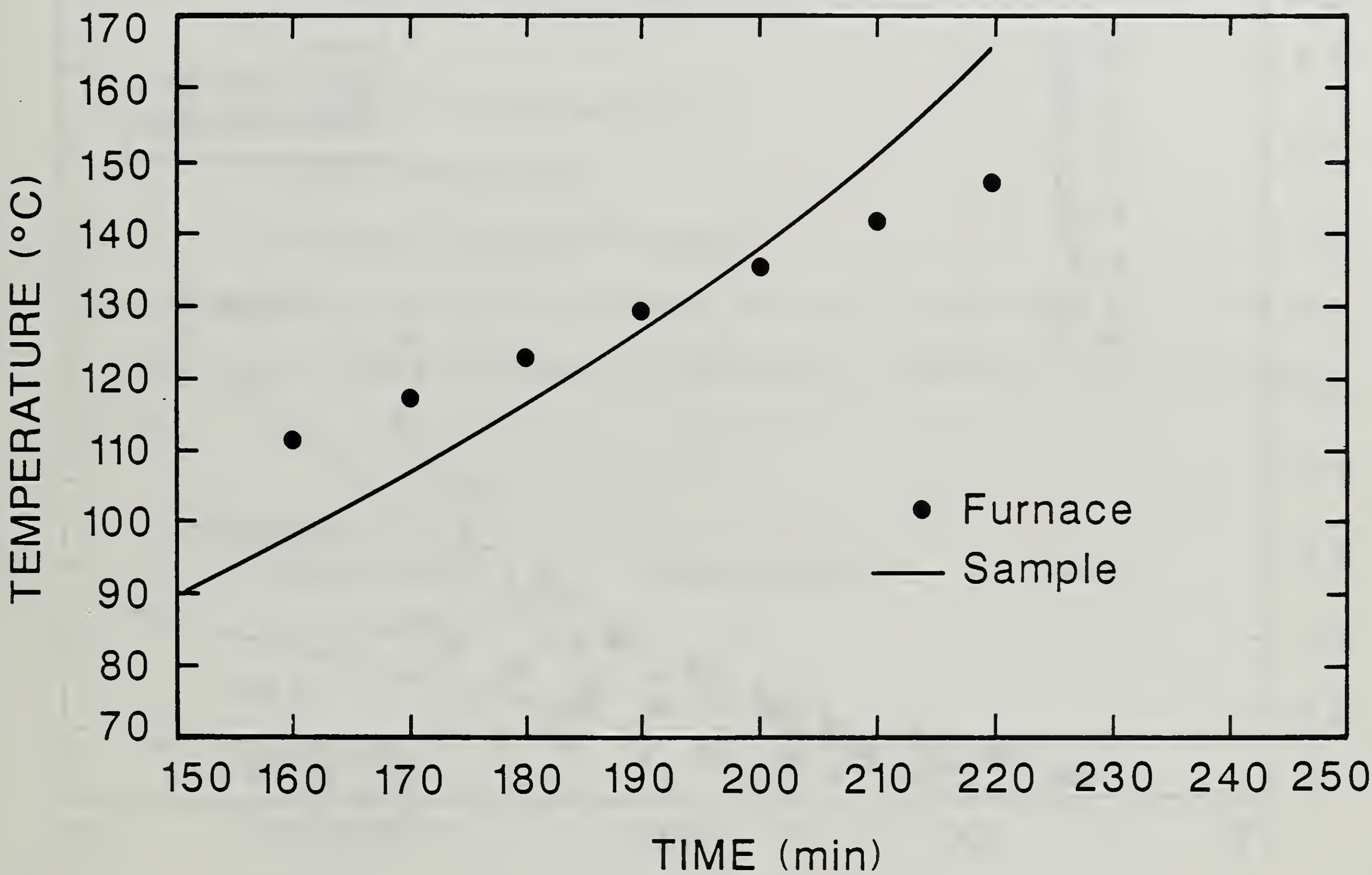


Figure 12 CPM test results for coal sample "G" heated at 0.61°C/min. Ignition occurred at 133°C.

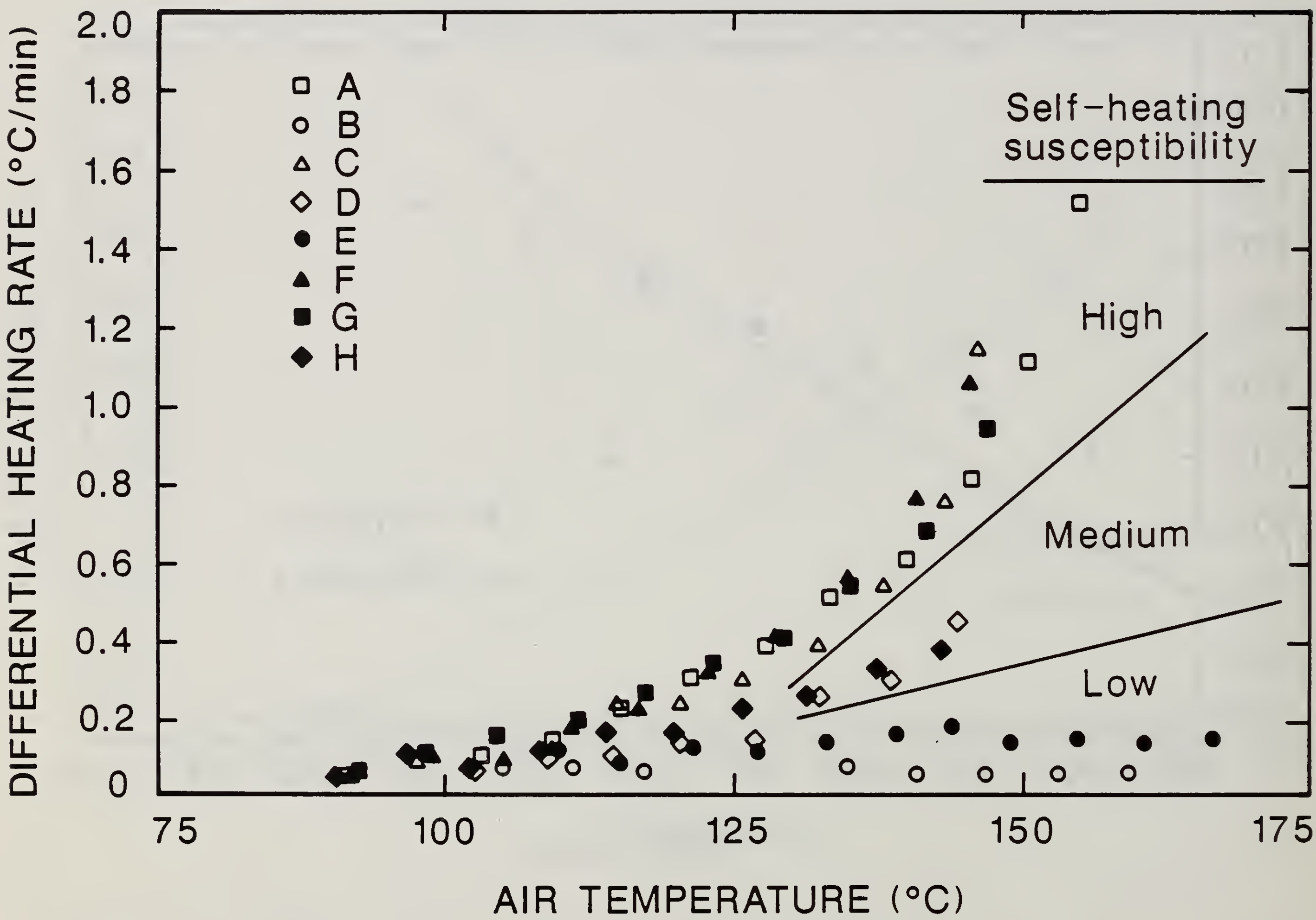


Figure 13 Plot of the CPM data for all eight coal samples showing the relationship between the furnace/sample temperature difference versus the furnace air temperature.

Appendix A

Rapid Appraisal of Spontaneous Combustion Assessed Liability (RASCAL) [2]

RASCAL provides a preliminary generalized indication of the degree of risk that can be obtained by considering the following parameters:

I-Rank of coal, as a factor of oxygen content;

II-Presence of pyritic sulphur minerals;

III-Hardness;

IV-Humidity of ventilating air;

V-Strata temperature;

VI-Unworked roof coal thickness.

These parameters are combined by taking the sum of parameters I, II, III, and IV. The sum of these parameters is multiply by thefactors from parameter V and VI.

I	Rank of Coal	Oxygen Content,%	Points
	Sub-bituminous	+15	18
		15 - 12	16
	Bituminous	12 - 10	14
	Weakly coking	10 - 8	12
	Coking	8 - 6	8
	Semi-anthracites	6 - 4	3
	Antracites	4 - 2	1
		<2	0

II	Presence of Pyritic Sulphur Minerals,%		Points
		+3.0	7
		3.0 - 2.0	5
		2.0 - 1.0	3
		1.0 - 0.5	2
		0.5 - 0.25	1
		<0.25	0
III	Hardness	Type	Points
		Very Friable	+ 4
		Friable	+ 2
		Medium Hard	0
		Hard	- 2
IV	Humidity of Ventilation Air	Saturation,%	Points
		+60	+ 2
		60 - 40	0
		40 - 20	- 2
		20 - 0	- 5
V	Virgin Strata Temperature	(°F)	Factor
		+105	5.0
		105 - 85	2.0
		85 - 70	1.25
		70 - 50	1.0
		32 - 50	1.0

VI	Unmined Roof Coal Thickness	(ft)	Factor
		+10	4.0
		8 - 10	3.5
		6 - 8	3.0
		4 - 6	2.5
		2 - 4	2.0
		>0 - 2	1.5

The overall Risk Factor (RF) is determined by:

RF=(I + II + III + IV) * V * VI,

Where:

Low Risk = Less than 10;

At Risk = 10 - 20;

High Risk= Greater Than 20.

Two Examples:

Parameters	Coal A Data	Coal A Points	Coal B Data	Coal B Points
I Coal Rank (oxygen)	12 %	14	5 %	3
II Pyrite Content	1.1 %	3	0.5 %	1
III Hardness	Friable	2	Medium Hard	0
IV Humidity	65 %	2	40 %	0
Total		21		4
V Roof Coal	2 ft	x 1.5	4 ft 6 in	x 2.0
VI Strata Temperature	60 °F	x 1.0	60 °F	x 1.0
RISK FACTOR		31.5		8

Appendix B

Translation of German Recommended Practices

Handbuch Arbeitssicherheit

Ruhrkohle AG

Nr.: 801 302 Blatt: 1 Stand: 12/78

Sachgebiet: Brandschutz unter Tage

Titel: Verhütung von Selbstentzündungsbränden

Contents:

0 Foreword

In collaboration with the Main Institute for Life Saving Systems for Mines in Essen, the Ruhrkohle AG has once more discussed the danger to underworkings stemming from spontaneous combustion, in a working committee of fire protection experts. The insights gained and the suggested measures are contained in the foregoing recommendations for the prevention of spontaneous combustion fires and they should serve as a contribution to a reduction of dangers to mine underworkings from spontaneous combustion of the coal.

The listed measures may be taken as needed. They represent various alternative solutions and, in this wide-range form, should be seen as a collection of possibilities of which the various enterprises may select effective measures, depending on the circumstances prevailing in their mines. The effective official regulations issued by mining authorities for the prevention of spontaneous combustion fires are not affected by these recommendations.

These recommendations will be updated in accordance with technical developments by later publications.

1 General Basis and Definitions of Terms

1.1 Explanation and Definition of Spontaneous Combustion

Coal oxidizes physically by the absorption or the accumulation of oxygen at the coal's surface. With a further penetration of oxygen into the coal, the temperature rises, unless the heat is drawn off. Oxygen enters chemical compounds and the results are oxidation products such as water (condensation spots) and low-temperature carbonization gases of carbon dioxide and carbon monoxide; later, these gases will also contain aromatic hydrocarbons (the smell of benzene and benzol).

Definition: The spontaneous combustion of coal is a physical-chemical process, producing oxidation products, with the temperature rising to such a level that smoldering fires will be created, which, if exposed and increased air having access to them, will begin to glow or to flare up.

1.2 Criteria and Their Influence on Spontaneous Combustion

Even Though all types of coal may attract and chemically combine with oxygen, not all lodes are in danger of spontaneous combustion. A spontaneous combustion will always depend on several criteria, the influence of which should be evaluated as follows:

- <u>Type of Coal</u>
  Shiny coal (vitrite and clarite) particularly tends to oxidation. This tendency increases with an increase of the volatile components and the humidity contents.
- <u>Grain Size</u>

Oxygen absorption increases with decreasing grain size, so that fine coal is the most endangered type.

- Pyrite Contents
  Pyrite oxidizes only in the presence of water and influences spontaneous combustion only in the lower ranges up to 325 K ≈ 50°C *)[1]
- Available Oxygen
  The speed of chemical reaction and inclination to oxidation as a rule increases with increasing availability of oxygen.
- Temperature and Temperature Curve
  Combustion temperature is between 380 K (107°C) and 500 K (227°C), dependent on the thickness of collected coal dust layers. Development of temperature in a spontaneous combustion fire is not in proportion with time. Beginning with a certain temperature threshold, which depends on the type of coal, the temperature rises much faster. The higher the initial temperature, the lower the difference to the critical temperature threshold. The temperature difference to the critical temperature threshold therefore becomes less and less as the depth and the rock temperatures increase.
- Lode Dips and Lode Thickness
  Observations made during a number of years have shown that the tendency to spontaneous combustion increases with increasing thickness and greater lode dips.
- Ventilation
  In addition to the effective ventilation currents, slow currents are caused because of the pressure difference. These slow currents, by introducing oxygen to residue coal remaining in abandoned workings, heighten the danger of spontaneous combustion. The less heat is drawn off by these slow currents and the more oxygen is introduced by them, the greater this danger becomes. The volume of critical slow currents is within the limits in which a steady oxygen supply to the center of oxidation is guaranteed, while not enough heat is removed so that the temperature increases steadily until the point of spontaneous ignition of the coal is reached.
- Type of Workings
  Compact stowing counteracts the formation of slow air currents and, therefore, spontaneous combustion. Given otherwise identical conditions, working in thrusts will further spontaneous combustion dangers.
- Type of Mining
  Retreating mining operations, because of fewer slow air current formations, is more advantageous than forward operations when it comes to prevent fires by spontaneous combustion.
- Organization of Recovery Operations and of Barraging
  The faster anf the more efficiently abandoned underworkings are stripped and sealed, the lower the danger of spontaneous combustion.

1.3 Points of Origin and Causes

---

[1] *) $t = T - T_0$ $n(°C) = n + 273.15[K]$ $0°C = +273.15\ K$ $0\ K = -273.15°C$

1.3.1 Points of Origin

Many years of experience have shown that the points of a possible spontaneous combustion are located wherever several criteria combine to favor the spontaneous combustion of coal. These are mostly:

- Leading and Trailing Edges;
- Coal Islands and Residual Coal Pillars;
- Thrust-working Operations with Parallel Lodes;
- Recovery-stripping Operations.

1.3.2 Causes

The folowing are possible causes:

- Slow air currents in connection with;
  - Residual Coal in Abandoned workings,
  - Crushed Coal in Rim Zones,
  - Gas-removal Drill Holes with Connections to Parallel Lodes,
  - Test and Relief Drill Holes,
  - Disturbanceareas with connections to open workings.

2 Measures for the Prevention of Spontaneous Combustion Fires During Planning

2.1 General

With a correct estimate and evaluation of the geological geometric situations, important measures can be agreed upon and can be initiated in the planning stage, by which the danger of spontaneous combustion can be reduced.

2.2 Measures Based on Lode Evaluation

When planning the mining operations, it should first be determined whether, in a certain lode,

- based on experience during operations
- or because of coincidence of several characteristics favorable to spontaneous combustion as to origin and cause,

there is reason to believe that the danger of spontaneous combustion will be expected.

It is therefore advisable to take the following measures, at the beginning of the planning phase:

- compilation and evaluation of experiences during operations
  - Entering fire-areas in plans of the lode to be worked and in the neighboring lodes
  - Experiences made in installations neighboring the lode to be worked
  - Evaluation of documents recording the CO-contents in previous elevations of the same lode.
- Compilation and evaluation of values influencing spontaneous combustion

- Type of coal (shiny coal, fibrous coal)
- Grain sizes
- Share of volatile components
- Moisture contents
- Sulfur contents, pyrite contents
- Tendency to oxidize

If the danger of spontaneous combustion must be expected, the following is to be observed during the planning stage:

- the selection of suitable mining equipment with proper machinery to completely mine the lode
- the selection of suitable face support methods for the complete mining of the lode
- the selection of the packing method, e.g. pneumatic packing in case of coal slippage from an adjacent roof
- the selection of suitable sealing methods to prevent slow air currents, e.g. securing of leading edges and sealing mines
- the barraging of the entire height after completion of mining (mining plan, stripping plan)

2.3 Measures Based on Geological Situations

- Disturbance zones require special measures to protect them from spontaneous combustion, since this danger is greater in their areas. These measures must be planned and prepared at an early stage (sealing, injections, cement injections after the torcret system).
- Coal of non-mined lodes in the roof which may come within the thrust range because of the short distance to the lode, increases the danger of spontaneous combustion. The measures for the reduction of this danger must be planned and initiated early: e.g. pneumatic packing, sealing of mines and leading edges.

2.4 Measures to be Considered when Designing Underworkings

- For many reasons, retreat mining operations are less subject to dangers of spontaneous combustion than forward mines.
- The leading edges of mining operations should not be located in disturbance areas.
- The distances between base mines and other mines should either be sufficient ($\approx 10 \cdot M$ at least 25 m) or be kept as little as possible.
- If this or other measures should create residual pillars, steps to prevent fires caused by spontaneous combustion must be taken. These measures include:
    - injection of solutions of hygroscopic salts containing surface-active agents,
    - treatment of surfaces with hygroscopic salts,
    - sealing by means of vaulting, backfilling, and packing (more information see 3.6).

- Long mine dips require effective measures because of the great air pressure differences at the abandoned workings during the advance to:
    - seal the leading edge;
    - seal the mining drifts;
    - maintain the cross sections for ventilation.

2.5 Measures to be Considered in Ventilation Technology-Planning

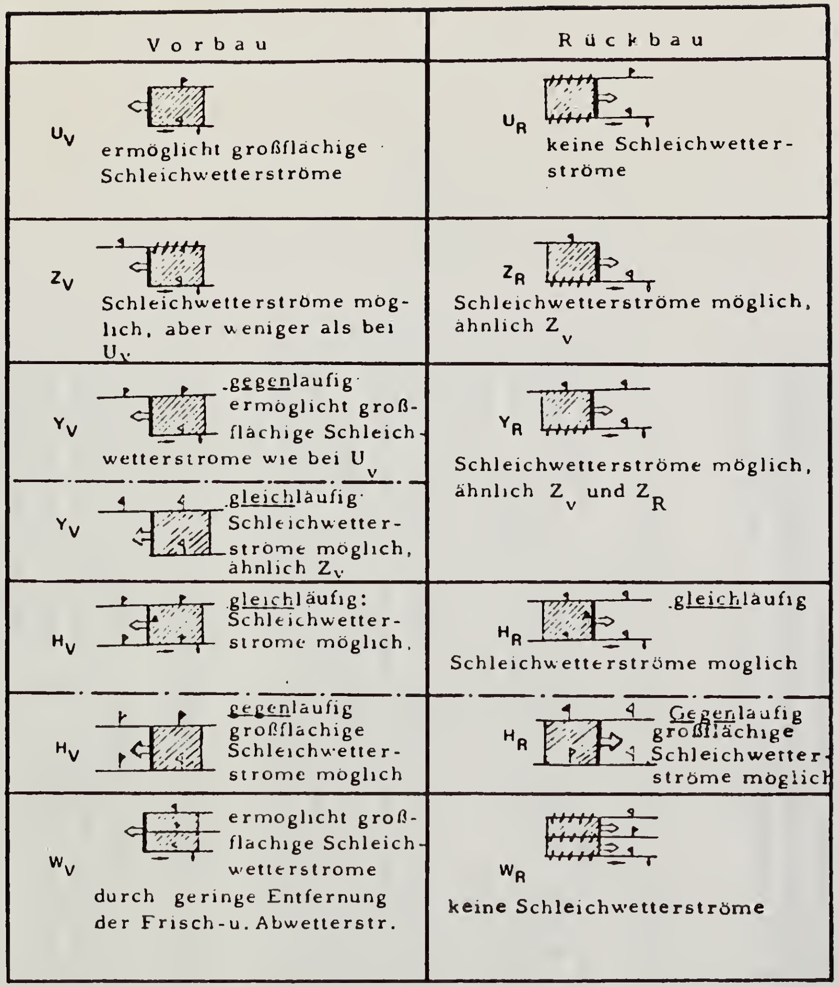
The danger of spontaneous combustion can be highly reduced if the following demands are taken into consideration in the planning phase:

- the avoidance of slow air currents
- the reduction of pressure differences at abandoned workings

The following measures are suited to meet these demands:

- sufficiently large ventilation cross sections
- avoiding throttles and narrow passages
- air-tight sealing of leading edges (No. 3.2)
- selection of suitable winning- and ventilation systems

The following viewpoints should be observed:



Keyed to Chart:

A Forword mining operations

A1 U_V: permits large-surface slow air currents

A2 Z_V: slow sir currents possible but fewer than U_V

A3 Y_V: running into opposite direction:
permits large-surface slow air currents as with U_V

A4 Y_V: running into same direction:
slow air currents possible, similar to Z_V

A5 H_V: same direction:
slow air currents possible

A6 H_V: opposite direction:
large-surface, slow air currents possible

A7 W_V: permits large-surface:
slow air currents because of short distance of fresh air and ventilation air

B Retreating Mining Operations

B1 U_R: no slow air currents

B2 Z_R: slow air currents possible, similar to Z_V

B3 Y_R: slow air currents possible, similar to Z_V and Z_R

B4 H_R: same direction:
slow air currents possible

B5 H_R: opposite direction:
large-surface, slow air currents possible

B6 W_R: no slow air currents

2.6 Measures to Secure Approaching and Trailing Edges

The approaching and the trailing edges of supports have increasingly become points of origin for spontaneous combustion.
The following are the causes:

- residual coal with a high share of fine coal
- crushed fine coal residue from the faces
- steady introduction of fresh air by slow air currents
- reduced heat evacuation by choked ventilation.

In order to reduce the danger of spontaneous combustion, therefore, it is necessary to plan and organize suitable measures to secure the approaching and the trailing edges. Dependent on the evaluation of the danger of spontaneous combustion, the following measures could be provided:

- Sealing
  - of the headings
  - of the stripped longwalls
  - of the lode trenches in front of and behind the approaching and the trailing edges, respectively.

  For this sealing operation, the following are particularly suitable materials:
  - hydraulically settling material
  - wooden posts with insulating foam back-fill
  - rock dust barriers

  In regions where there is particular danger, the sealing operations could be complemented by a back-filled collar accross the entire mine circumference.
- Treatment of approaching and trailing edges with hygroscopic salts:
  - by applying it in powdered form on the coal face;
  - by injection of solutions of hygroscopic salts containing surface-acyive ingredients into the approaching and the trailing edges;
  - by sprinkling the floor with flaked material.

2.7 Measures for the Prevention of Spontaneous Combustion Fires During the Planning Stage

If the criteria which further spontaneous combustion are properly weighed and evaluated in the planning phase, such possible danger can be discovered early (see Planning Aids in the appendix to these recommendations). As soon as these insights have been gained, measures can be planned by which spontaneous combustion can either be prevented or greatly reduced.

3 Measures for the Prevention of Spontaneous Combustion Fires During Operations

3.1 General

Basically, two types of measures must be taken to prevent fires caused by spontaneous combustion:

- measures which have been planned because of foreseeable influences
- immediate steps which may become necessary because of unforeseeable and suddenly occurring events.

Quite generally, measures are planned prior to the start of operations, and dealing with the various phases of the operation, which can prevent fires by spntaneous combustion, given normal conditions and a careful execution of these measures. If these conditions should change, or unforeseen influences should develop which favor spontaneous combustion, it will be necessary to provide supplemental or additional measures during the operations and in due time, so that this danger of spontaneous combustion can be banned even under these altered conditions. Depending on the evaluation of the danger of spontaneous combustion, the measures listed in numbers 3.2 to 3.10 are suitable for both of these cases.

3.2 Securing the Approaching Edges

3.2.1 Sealing

When sealing the approaching edge, normally three sections must be observed:

Headings
Approaching Edge

3.2.1.1 Sealing Trench of Lode Walls

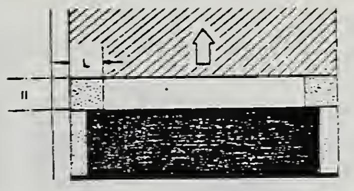
The Trench of the lode walls should be sealed about 5 - 10 m behind the approaching edge, by providing air-tight insulation against the coal outcrop.

The following materials are suitable, with their value increasing as follows:

- wooden posts with a rock-dust barrier
- wooden posts with foam backfill (e.g. Iso-foam)
- a dyke of hydraulically settling material (B˜2 M)
- collars of hydraulically settling material across the entire circumference of the mine.

3.2.1.2 Sealing of Heading Entrances

The heading-entrances should be sealed off across the entire width of the heading.

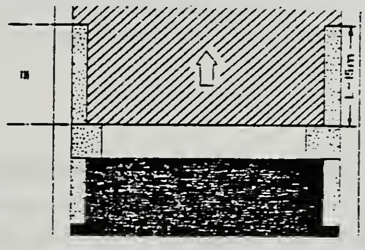


The following materials are suitable, with their value increasing as follows:

- Closing plugs made of
    - rock dust (L~5 M)
    - hydraulically settling material (L~3 M)
- A dyke of hydraulically settling material extending the seal of the heading

3.2.1.3 Sealing Trench of Lode Walls Against the Thrust-working Field in the Area of the Approaching Edge

The wall trench of the approaching longwall must be sealed off along a distance of a least 15 m immediately adjoining the sealing of the heading.

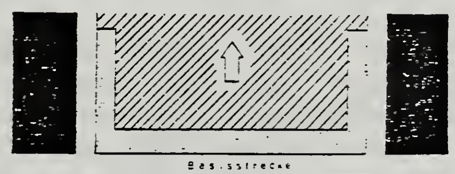


The following materials and means are suitable for this purpose:

- rock dust barriers (B~3 M)
- wooden posts with iso-foam back-fill
- a parallel dam made of hydraulically settling material (B~2 M)

3.2.1.4 Securing the Approaching Edge Along Lode-parallel Mines

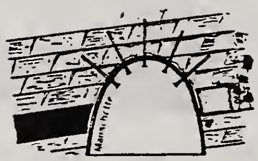
Whenever longwalls are developed immediately out of the base mine or lode-mine, similar steps to the measures listed in 3.2.1.3 must be taken to provide a ventilation seal across the entire approaching edge, with hydraulically settling materials being given preference for reasons grounded in ventilation- and fire-prevention technology.

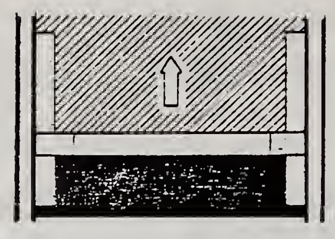


3.2.2 Special Measures

3.2.2.1 Collar with Back-fill

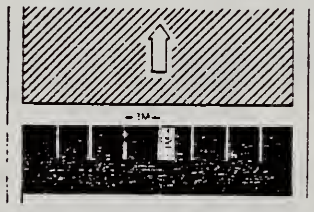
If the sealing measures enumerated thus far should not guarantee an air-tight seal of the surrounding edges, (for instance in very loose roof lodes in the area of the trench) the insertion of a collar across the entire mine circumference is recommended in the area of the approaching edge insulation, and back-filling it with hydraulically settling material.





3.2.2.2 Treatment of Approaching Edge with Hygroscopic Salts such as $CaCl_2$ or $MgCl_2$, Containing Surface-Active Agents

Whenever the danger of spontaneous combustion has already been identified, additional safeguards are recommended for the approaching edge by treatment with saturated solutions of hygroscopic salts such as $CaCl_2$ or $MgCl_2$ containing surface-active agents.



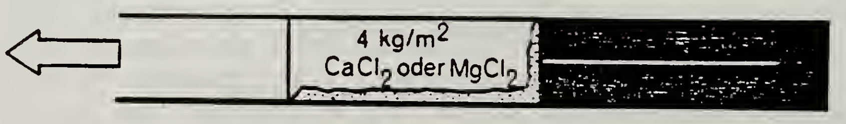
The solutions with the surface-active agents should be injected into the approaching edge which is to be protected by means of drill holes

- at a distance of ~ 3 ·M from each other
- of at least ~ 3 ·M depth.

The injection must be performed with pressures which are adapted to counter-pressure of the coal. This should prevent a loosening of the approaching edge and should result in the highest possible degree of saturation in the injected area. Experience has shown that these pressures range from 20 to 100 bar.

Injection should continue until the solution emerges from the face of the coal. The ijected solution should - if possible - be no less than 10 ℓ/m^3 coal, which corresponds to a value of ~ 2.5 kg salt/t coal.

In addition to this injection of salt solutions with surface-active agents, a surface treatment of the approaching edge with suitable hygroscopic salts ($CaCl_2$) may be performed. In this operation, at least 4 kg powder or flakes for each m^2 surface of exposed coal floor and the face of the leading edge within the heading are needed for a sprinkling operation.



3.3 Ventilation in Operating Mine

During the operations, all possible measures must be applied and made permanently effective to keep the pressure difference at the abandoned workings as small as possible and to prevent slow air currents.

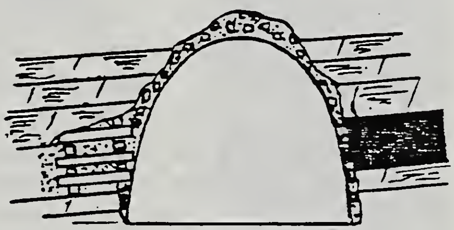
Some of these measures are:

- maintaining the mine-cross-sections
- maintaining the face openings as planned
- avoiding unnecessary obstructions to the ventilation (door frames, material)
- sealing of trenches so that as little slow air currents can reach the abandoned workings. This measure is better suited for maintaining of the mine-cross-sections, and a better flow of service ventilation through the mine is guaranteed (No. 3.4)
- maintaining the necessary service ventilation (not to be exceeded)
- adapting the service ventilation to altered mining or gas-drainage conditions

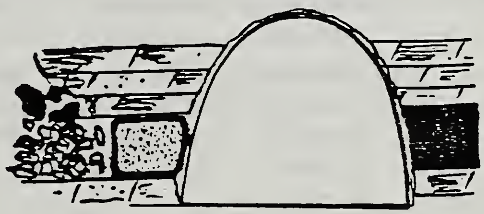
3.4 Sealing of Wall Trenches

In order to prevent slow air currents, and supposing a recognized existing danger of spontaneous combustion, the wall trenches should be sealed directly subsequently to the securing of the approaching edges. The following processes are suitable for this purpose, and their effectiveness is increased in the following order:

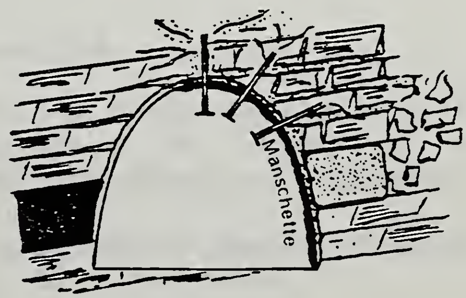
- Filling hollow spaces in the wall trenches with foam material (e.g. Iso-foam)



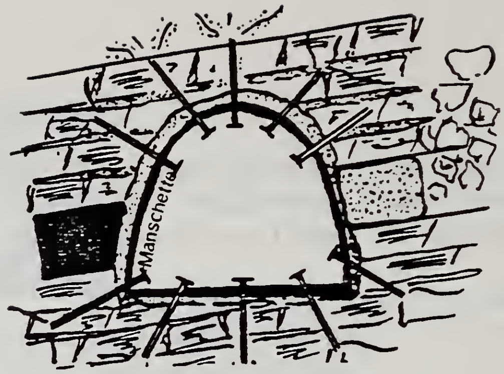
- Filling wall trenches with parallel dams of dam setting building material. Methods permitting a close connection with the hanging lode and guaranteeing early load bearing properties should be preferred



- Additional sealing of the shore seam by vaulting (panelling, sprayed mortar or similar methods) and back-filling with subsequent compression with dam setting material



- Sealing of entire circumference of mine, in some special cases even including the floor portion, by vaulting, back-filling and subsequent compression with dam setting material.



3.5 Observation of Geological Disturbances

Geological disturbances increase the danger of spontaneous combustion and require additional preventive measures. Some of these are:

- leaving as little as possible residual coal in abandoned workings;
- filling cavities in the area of disturbance, not with wood but with non-flammable material, e.g. with foam, hydraulically setting dam materials, light-weight concrete barriers;
- in the case of geological faults in the mine area, a pre-determined stretch will be selected, along which stretch - and in zones preceeding and following it - special steps will be necessary. It is recommended to use vaulting, bak-filling and compression with setting dam materials;
- treatment of the loose rock area in the disturbance zone with saturated solutions of hygroscopic salts, such as $CaCl_2$ or $MgCl_2$, with these solutions containing surface-active ingredients. The solution can be introduced into the abandoned workings by means of lances from the direction of the longwall opening, so that the residual coal is wetted. For this purpose, suitable, closeable, openings (50 mm in diameter) in a shield-type support should be provided, with proper suitable connection means.

3.6 Treatment of Residual Pillars

Residual pillars which are the result of mining activities tend to contribute to the danger of spontaneous combustion because of their less compact composition due to the mining pressure.

Residual pillars of this kind are:

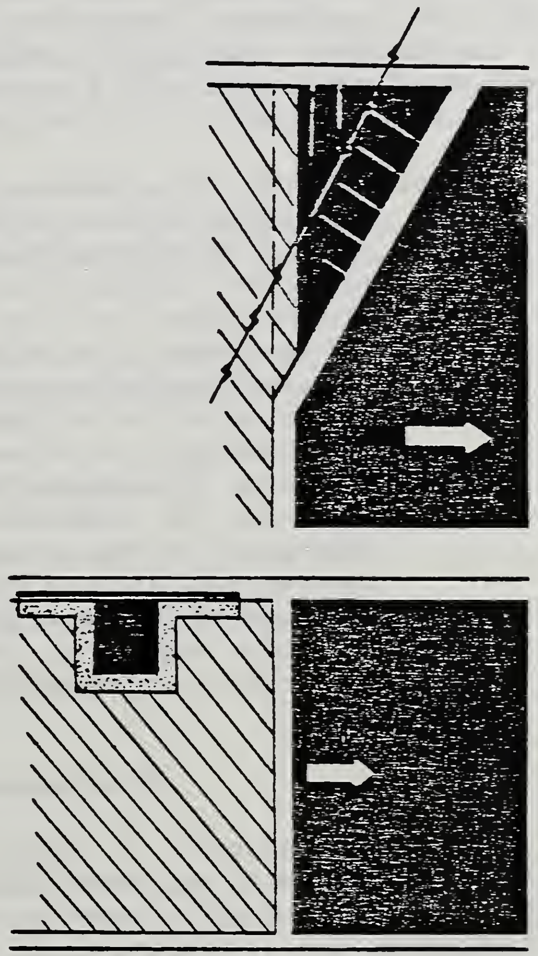
- geological coal islands

- safety pillars caused by support construction and ventilation techniques (mostly parallel to the lode axis)
- residual pillars caused by the mining course, for instance because of slewing methods.

Residual pillars require special measures to prevent spontaneous combustion:

- injection of saturated solutions of hygroscopic salts such as $CaCl_2$ or $MgCl_2$ with surface-active components into the remaining residual pillars.
  When doing this, the following must be observed:
  - the drill holes should be inserted from all sides, if possible;
  - the distance between boreholes and their depth must be adapted to the solidity and the looseness of the coal,
  - the highest possible saturation should be achieved with the lowest possible pressures (see No. 3.2.2.2)

- Sealing of residual pillars with setting insulating substances, e.g. by vaulting, or filling of neighboring mines



- Surface treatment by covering with powdered suitable hygroscopic salts ($CaCl_2$) the coal faces of residual pillars in several repeated operations, using 4 kg/m^2 of powder.

- Surface treatment by repeated application of pasty dust-fixing materials

After taking these preventive measures, these residual pillars must be specially supervised to prevent fires.

The following are suitable methods, among other things:

- the introduction of sensor blow pipes and the taking of probes at regualr intervals
- monitoring the temperature by means of infra-red and drill hole thermometers

- observation of CO-generation in the free cross section of the neighboring mine

3.7 Sealing of Abandoned Underworkings

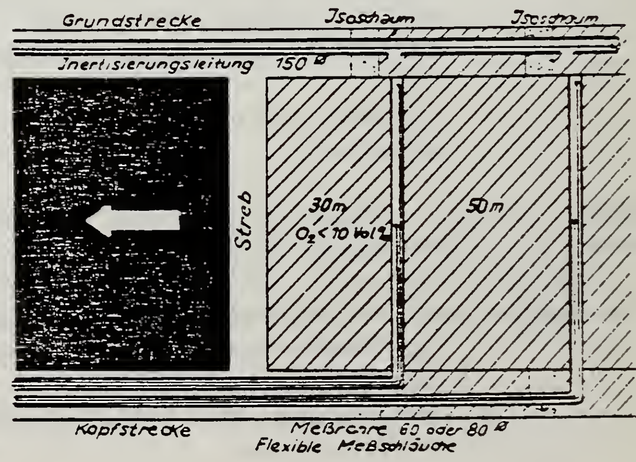
Abandoned underworkings which are still open have proven to be points of origin for spontaneous combustion fires. Insufficient heat drainage because of insufficient ventilation will, if they last long enough, lead to spontaneous combustion with a very high degree of probability. Underworkings of this kind, therefore, require particular attention.

In principle the following measures are deemed necessary:

- adherence to the guidelines of the LOBA NW for barraging and sealing of underworkings,
- sufficient ventilation during the stripping phase,
- timely start of the stripping phase after abandoning the underworkings to be stripped,
- expedient stripping operations,
- selection of a suitable location for the sealing, so that the underworkings can be sealed permanently, solidly and tighly,
- selection of suitable buttresses and dam building materials,
- selection of suitable dam length dependent on the pressure difference in the ventilation and on the degree of looseness of the surrounding rock formation,
- observation of instructions regarding the use of dam building materials and the use of the required operational means,
- observation of instructions regarding long-range sealing.

3.8 Preventive Inertization

When mining for topcoal or winning operations in parallel lodes with roof coal, from which coal can reach the loose rock area, there is great danger of spontaneous combustion. Based on experiences gained abroad, this danger can be limited by the preventive continuous insertion of inert gas into the loose rock area.



Thus far, the experiences with inertization relate to retreating mining operations only.

The liquid nitrogen is vaporized in a cold process above ground, inder normal atmospheric conditions and taken into the mining site by means of steel pipes with diameters up to 150 mm.

The pipeline along the ventilation channel takes the nitrogen gas to the loose rock area, flowing at 500 m^3 per hour and, by reducing the oxygen contents to 10-15 %by volume, reduces the danger of spontaneous combustion. Within the loose rock area, perforated steel pipes are installed every 50 m, having diameters of 50 to 80 mm, from which air samples can be drawn by means of flexible plastic tubes.

3.9 Monitoring Fire Protection Parameters

3.9.1 General

The measuring, compiling and the evaluation of parameters for an early detection of spontaneous combustion fires have become ever increasingly important.

It is therefore advisable that operations which must consider a possible spontaneous combustion of the coal be monitored at regular intervals.

3.9.2 Possibilities of Supervision

The following parameters must be monitored especially, so that beginning spontaneous combustion fires can be detected:

- CO-generation (ppm-contents, or, respectively, amount of CO generated in ℓ/min)
- Ventilation current (slow air current)
- Pressure difference
- Temperature development

The required measurements can be conducted by means of

- portable measuring devices
- complete analysis
- automatic and, if needed, recording measuring devices.

Details regarding methods and equipment can be found in the following bulletins and publications:

- Bulletin dealing with the use of CO-metering devices and pertinent amendments 1975 and 1977
- Bulletin for the evaluation of foul gas analysis
- Training of Mine Rescue Teams Parts I and II (1973 and 1974)
- Training for Gas Teams (1975)

3.9.3 Special Supervisory Measures

Especially endagered regions with increased danger of spontaneous combustion require special supervisory measures.
These regions include:

- Approaching and trailing edges,
- Zones of disturbances,
- Residual pillars and,
- Partially mined coal and parallel hanging lodes.

The following are suitable special measures:

- the taking of samples from sensor blow pipes,
- the taking of samples from gas drainage pipes,
- measuring of temperatures (infra-red or drill hole thermometer),
- shortening the time intervals of sample taking,
- additional use of stationary metering devices.

These measures should be decided on in each individual case and should be well coordinated.

3.10 Information and Instruction

The effectiveness of the planned and executed measures for the prevention of spontaneous combustion fires will depend on thorough instruction and exchange of information among the responsible personnel.
These are:

- the plant management,
- the staffs for planning and operational areas,
- the safety and mining units,
- operational supervisory personnel (fire bosses, gas men, foremen),
- supervisory personnel in the affected mines.

The instruction of this personnel is the responsibility of the plant management, in cooperation with the responsible staff and expert personnel offices. It should be repeated in set intervals.

Newly hired persons must be advised by instructed personnel of the special dangers of spontaneous combustion before they take over certain duties.

For a coordination of the planned measures to be taken, comprehensive information of the responsible persons is absolutely necessary. It is recommended that, for this purpose, a complete information system and a written information service regarding planned or applied changes be set up.

4 Publications

Babokin:
Mining losses in coal mining as cause for the generation of spontaneous combustion fires
International Conference Czechoslovakia, October 1966

Both and Weinheimer:
A remarkable case of a spontaneous combustion fire in the cooperative mine HausAden
Glueckauf, 5 Feb 76

Both and Stark:
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Both:

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Buecher:
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Chamberlain and Hall:
Examination of Factors preventing or furthering spontaneous combustion of coal
Special Printing of the National Coal Board

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Spontaneous Combustion of Coal; Examination of Inhibitors and Preventors
Colliery Guardian 1974, March No. 3, p. 79/82

Externbrink and Lewer:
Reduced danger of spontaneous combustion by use of calcium chloride mineral powder
Glueckauf, 1971, No. 17, p. 652/653

Flachowsky and Voelkel:
Some methods for the fire prevention and fighting in the VED coal mine Oelsnitz
Bergakademie 19 (1967) No.1, p. 16/21

Foelfoeldy:
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Information of Hungarian Institute for Mining Research, 1970, No. 13, p. 153/159

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Lewer:
Means for the prevention of spontaneous combustion of coal
Disclosure Document 2 129 462 (German Patent Application 4 Jan 73)

Lewer:
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(Disclosure document 2 419 144, German Pat. Application 30 Nov 75)

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Institut Vost N II
(Scientific Research Institute for Mine Safety East)

Matusek:
Model for the criteria to evaluate hazards of spontaneous combustion of coal in longwalls
Paper D 4, International Conference Varna 1977

Mueller, R.:
Method for the prevention of spontaneous combustion fires in abandoned workings and loose rock areas of Saarbergwerke AG
Glueckauf 103 (1967) No. 22, p. 1125/31

Dr. Muenzner:
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Glueckauf Research Magazine, April 1972, Part I and Part II

Dr. Muenzer and Peters:
Adiabatic oxidation of hard coal to characterize its spontaneous combustion behavior
Brennstoff-Chemie, Vol. 50 (1968)

Dr. Muenzer and Peters:
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Petrochemie, 22nd Year

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Kirkless, Wigan

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The prevention of spontaneous combustion of coal in the mines of Combine "Artemugol"
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Dr. Sebor and Hofbauer:
Chemical methods for the prevention and fighting of fires in mines
VEB Deutscher Verlag Fuer Grundstoffindustrie 1962

Siepmann:
The saturation of residual pillars with solutions of hygroscopic salts
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N.N.:
Measures for the prevention of spontaneous combustion fires in mines
Information of BAG
Niederrhein, September 1973

Appendix

Planning Aids for the Evaluation of Danger of Spontaneous Combustion

1 General

Spontaneous combustion of coal is more or less influenced by several geological conditions and measures taken in the course of mining operations singly or in combinations thereof. In the presence of several combined criteria, the danger of spontaneous combustion increases. We have practical experiences regarding the influence of certain criteria and their effect on the spontaneous combustion and also regarding the influence of a combination of them, but proven scientific knowledge is still outstanding.

As a planning aid for the evaluation of a possible danger of spontaneous combustion we have, for the time being, supplied a system whereby, with the aid of a form (see enclosure 1) the experiences gained may be utilized while there is no claim made that the statements made are scientifically proven. As soon as additional experience and insights have been gained, based on continuous observation and intensive research, this planning aid will be examined from time to time as to its applicability and, if needed, will be updated to represent the state of the latest knowledge.

2 Instructions for Use of the Planning Aid

The evaluation of a possible danger of spontaneous combustion for a mining operation begins with the selection of design alternatives. After selecting one or several possibilities, a check is made how conditions furthering spontaneous combustion and other conditions affect these alternatives.

The form (enclosure 1) contains a listing of 10 criteria which, according to experience, have a more or less pronounced influence on the spontaneous combustion of coal. Their vertical arrangement represents their relative weight and does not claim general applicability. Dependent on experience and the evaluation of special conditions in the individual mines, the experts responsible may weigh these criteria with numbers 1 to 10, according to their own judgement. The example given in the form of Enclosure 2 which has been filled out, therefore, is no more than a rough sketch of possible evaluations. The criteria are divided into two categories. Those who cannot be influenced: geological, tectonic, and petrographic conditions (group 1) and those which can be influenced by measures of fire protection and ventilation techniques with effects on the spontaneous combustion of coal (group 2).

Group 1

Depending on their type and extent, the conditions which are beyond influence, influence the spontaneous combustion hazard and must be evaluated accordingly. ere, too, the horizontally arranged evaluation figures from 1 to 10 in the form for different areas within the criteria represent no more than a rough suggestion. With different experiences in a mine, the responsible personnel may set them according to their own judgement.

When evaluatin the influence of the type of coal on the spontaneous combustion behavior,

- the degree of carbonization,
- the petrographic structure, and
- the share of volatile compounds

must be taken into consideration. In individual cases, certain types of coal may call for a higher evaluation, if there exist corresponding experiences made in the mine.

Disturbances and small-area tectonics should be evaluated, so that characteristics:

- thickness of the fault area,
- residual coal in abandoned workings,
- structure of coal in the fault area,
- situation of the fault areas relative to the mining lodes and approaching edges,
- increased pyrite contents in the neighborhood are considered accordingly.

Parallel hanging lodes must be evaluated according to:

- the distance from the supported lode
- their thickness and
- their pyrite content.

Group 2

This group includes fire protection measures and ventilation techniques which exert an important influence on the spontaneous combustion, but which may be decisively influenced by the operations. Their evaluation will be made after qualitative judgement of the measures taken. The responsible technical personnel will have to determined for each design alternative whether, because of ventilation or geometrical conditions,

- the treatment of residual pillars,
- the execution of sealing operations,
- the securing of approaching and trailing edges

will be required.

According to the prevailing opinions here and abroad, slow air currents are an important criterion for the generation of spontaneous combustion fires. The knowledge regarding the extent and the nature of dangerous slow air currents is still negligble and should be increased by purposeful investigations. The defineable air currents in drill holes must be seen as a special form of slow air currents, with the holes serving the purpose of gas drainage and testing, as well as for the relaxing of dangers of pressure bursts. Because of their intentional introduction of oxygen and the insufficient drainage of underground heat, they are a latent hazard of spontaneous combustion.

The differentiated evaluation of the danger of spontaneous combustion based on the sums and the sub-division into four danger groups is based on past operational experience. After the system has been tested and now experiences have been gained, the limits for danger groups are to be re-examined and, if necessary, newly defined.

Enclosure 1

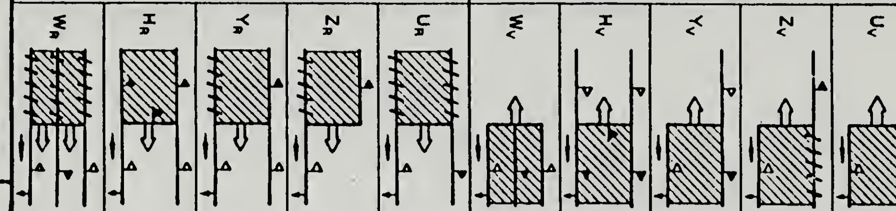
Planungshilfe für die Bewertung der Selbstentzündungsgefahr

Rechengang :
1. Bewertung der Kriterien nach Gegebenheit
2. Multiplikation von Wichtung und Bewertung
3. Eintragen des Faktors WxB in die gewählte Zuschnittsalternative
4. Summierung der Faktoren WxB
5. Bewertung der Zuschnittsalternative

Zeichen
- ⇨ Abbaurichtung
- Förderrichtung
- Einfallen
- Frischwetter
- Abwetter

Kriterien	Wichtung (W)	Bewertung (B) 0	1 – 2	3 – 4	5 – 6	7 – 8 – 9 – 10
Kohlenart			Anthrazit/ Eßkohle	Gaskohle Gasflammk.	Fettkohle	
Einfallen			0 - 40^g	40 - 60^g		60 - 100^g
Flözmächtigkeit			< 1,40 m	1,40 - 2,00 m	2,00 - 3,00 m	> 3,00 m
Pyriteinlagerung		nicht vorhanden	vereinzelt	regelmäßig		stark
Störungen Kleintektonik		keine	gering	mittel		stark
Begleitflöz im Hgd. /Topkohle		nicht vorhanden	wenig	mittel		stark
Kohleninseln Restpfeiler		nicht vorhanden	abgedämmt	behandelt oder abgedichtet		zerdrückt, freiliegend unbehandelt
Abdichtungsmaßnahmen		nicht erforderlich	hydr. abb. Material	sonstiges Material Staubriegel u. a.		erforderlich aber nicht mitgeführt
Anlauf- und Auslaufkantensicher.		nicht erforderlich	hydr. abb. Material	sonstiges Material Staubriegel u. a.		erforderlich aber nicht vorhanden
Schleichwetter		nicht vorhanden	unbedeutende Ströme			bedeutende Ströme

Abbauführung



	rückbauartig										vorbauartig									
	W_R		H_R		Y_R		Z_R		U_R		W_V		H_V		Y_V		Z_V		U_V	
	B	WxB	B	WxB	B	WxB	B	WxB	B	WxB	B	WxB	B	WxB	B	WxB	B	WxB	B	WxB
Kohlenart																				
Einfallen																				
Flözmächtigkeit																				
Pyriteinlagerung																				
Störungen Kleintektonik																				
Begleitflöz im Hgd. /Topkohle																				
Kohleninseln Restpfeiler																				
Abdichtungsmaßnahmen																				
Anlauf- und Auslaufkantensicher.																				
Schleichwetter																				
ΣW x B																				

Betriebspunkt: Flöz:	**Maßnahmen:** Anlaufkantensicherung:
Bauhöhe:	Abbaustreckenbegleitdämme:
Abteilung:	Restpfeilerbehandlung:
Sohle:	Schleichwetterverringerung:
Abbauführung:	Bewetterungsart:

Bewertung : Summenzahlen von 0 bis 50 : geringe Selbstentzündungsgefahr
50 bis 100 : beginnende "
100 bis 200 : mittlere "
200 bis 300 : große

Bemerkungen :

Translation Key for Enclosure 1

<A> Planning Aid for the Evaluation of Danger of Spontaneous Combustion

<S> Direction of Mining Operation
Retreating — Advancing

<B> Calculation
1. Weighing the criteria according to existing conditions
2. Multiplying importance and evaluation
3. Entering the factor Importance x Evaluation into the selected design alternative
4. Summarizing factors I x E above
5. Evaluating design alternative

<C> Legend
Mining operations, direction
Hauling direction
Dips
Fresh air
Exhaust ventilation

<D> Criteria <E> Weight (i.e. importance) <F> Evaluation (B)

<G> Type of Coal — Anthracite/----Gas Coke-----------Bituminous Coal
Forge Coal-----Open Burning Coal

<H> Dips

<I> Lode Thickness

<J> Pyrite Contents — None----Occasional---Regular---High

<K> Disturbances/ Area Tectonics — None------Minor------Medium----High

<L> Parrallel lode in roof/top coal — None-----Little------Medium----High

<M> Coal Islands — None----Dammed Up---Treated or sealed----Crushed,freely exposed,untreated

<N> Sealing Measures — Not Needed--Hydr.setting material--Other Material dust barrier etc.--Needed, but not performed

<O> Securing of Approaching and Trailing edges — Not Needed--Hydr.setting material--Other Material dust barrier etc.--Needed, but not performed

<P> Slow Air Currents — None-----Unimportant currents----Important currents

<Q> Location of operation:
Lode:
Height:
Department:
Sole:

<R> Measures:
Securing approaching edges:
Parallel dams to mining wall:
Treatment of residual pillars:
Reduction of slow air currents:

<T> Evaluation: Sums From
0 - 50 : little danger of spontaneous combustion
50 - 100 : beginning danger of spontaneous combustion
100 - 200 : medium danger of spontaneous combustion
200 - 300 : great danger of spontaneous combustion

<U> Remarks:

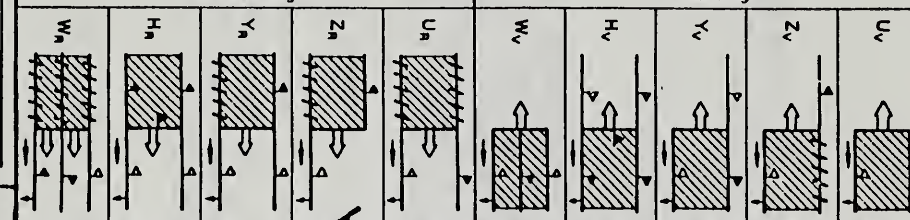
Enclosure 2

Planungshilfe für die Bewertung der Selbstentzündungsgefahr

Rechengang :
1. Bewertung der Kriterien nach Gegebenheit
2. Multiplikation von Wichtung und Bewertung
3. Eintragen des Faktors WxB in die gewählte Zuschnittsalternative
4. Summierung der Faktoren WxB
5. Bewertung der Zuschnittsalternative

Zeichen:
- ⇨ Abbaurichtung
- ⟵ Förderrichtung
- ⊤ Einfallen
- ▷ Frischwetter
- ▶ Abwetter

Abbauführung: rückbauartig (W_R, H_R, Y_R, Z_R, U_R); vorbauartig (W_V, H_V, Y_V, Z_V, U_V)



Kriterien	Wichtung (W)	Bewertung (B): 0	Bewertung (B): 1–10	W_R B	W_R WxB	H_R B	H_R WxB	Y_R B	Y_R WxB	Z_R B	Z_R WxB	U_R B	U_R WxB	W_V B	W_V WxB	H_V B	H_V WxB	Y_V B	Y_V WxB	Z_V B	Z_V WxB	U_V B	U_V WxB
Kohlenart	1		1–2: Anthrazit/Eßkohle; 3–4: Gaskohle Gasflammk.; 5–6: Fettkohle									5	5									5	5
Einfallen	2		0 - 40g; 40 - 60g; 60 - 100g									1	2									1	2
Flözmächtigkeit	3		< 1,40 m; 1,40 - 2,00 m; 2,00 - 3,00 m; > 3,00 m									3	9									3	9
Pyriteinlagerung	4	nicht vorhanden	vereinzelt; regelmäßig; stark									0	0									0	0
Störungen Kleintektonik	5	keine	gering; mittel; stark									4	20									4	20
Begleitflöz im Hgd. /Topkohle	6	nicht vorhanden	wenig; mittel; stark									0	0									0	0
Kohleninseln Restpfeiler	7	nicht vorhanden	behandelt abgedämmt oder abgedichtet; zerdrückt freiliegend unbehandelt									0	0									0	0
Abdichtungs-maßnahmen	8	nicht erforderlich	hydr. abb. Material; sonstiges Material Staubriegel u. a.; erforderlich aber nicht mitgeführt									0	0									5	40
Anlauf- und Auslaufkantensicher.	9	nicht erforderlich	hydr. abb. Material; sonstiges Material Staubriegel u. a.; erforderlich aber nicht vorhanden									0	0									2	18
Schleichwetter	10	nicht vorhanden	unbedeutende Ströme; bedeutende Ströme									0	0									5	50
ΣW x B													36										144

Betriebspunkt:

Flöz: Ernestine

Bauhöhe: 20

Abteilung: 3 NW

Sohle: 10. (-950 m)

Abbauführung: Alternative Rückbau-Vorbau

Maßnahmen:

Anlaufkantensicherung: hydraulisch abb. Material

Abbaustreckenbegleitdämme: Pfeiler (Altschwellen) Isoschaum

Restpfeilerbehandlung: entfällt

Schleichwetterverringerung: Isoschaum

Bewetterungsart: U_R - U_V

Bewertung : Summenzahlen von
- 0 bis 50 : geringe Selbstentzündungsgefahr
- 50 bis 100 : beginnende "
- 100 bis 200 : mittlere "
- 200 bis 300 : große

Bemerkungen : bei U_R = geringe Selbstentzündungsgefahr
bei U_V = mittlere Selbstentzündungsgefahr zu erwarten

Translation of Additional Terms from Enclosure 2

The second form of the Planning Aid is filled out, as an example, with data for a fictitious mine. Translation applies to lower portion of the form.

<A> Alternative
retreating and advancing

<B> Hydraulically setting material

<C> Pillars (old ties) foam

<D> Not applicable

<E> Iso-Foam

<F> U_R - U_V

<G> with U_R = little danger of spontaneous combustion
with U_V = medium danger of spontaneous combustion must be expected

Appendix C

The Canadian System

Evaluation of Coal Mine Susceptibility to Spontaneous Combustion

This system for predicting the likelihood of spontaneous combustion in coal mines is based on the calculation of a Risk Index that is the combination of two factors - the nature of the coal and the mine environment. The product of these factors is the Risk Index. It is a single valued index that corresponds to the anticipated likelihood of spontaneous combustion incidents.

$$\text{Risk Index} = (\text{Liability Index}) \times (\text{Environmental Index}) \qquad (1)$$

The nature of the coal to self-heat is measured by the Crossing Point Method developed by Feng, et al [1]. This method experimentally determines the relative ignition temperature at which measureable self-heating occurres. A Liability Index or Figure of Merit is calculated by

$$\text{Liability Index} = \frac{\text{Ignition Temperature}}{\text{Furnace Heating Rate}} \times 100 \qquad (2)$$

Liability Index for Coal

Index	Rating
>10	High
5-10	Medium
0-5	Low

The ignition temperature is the temperature at which the furnace air and the sample core are equal. The furnace air is increased at a steady rate until the sample core temperature crosses the furnace air temperature.. The results of equation (2) are indicative of the coal sample's susceptibility to self-heat.

The Mine Environment Index is determined by classifying the mine environment according to three parameter: coal loss; fissuration; and ventilation pressure differential. A Mine Environment Index is obtained by reading a value from a chart the lists the three parameters and the index value.

The Mine Environment Index is determined by:

Mine Environment Index

Group	Coal Loss	Fissuration	Ventilation Pressure Differential	Index	Rating
A	Normal	Natural	Normal	1	Low
B	High	Natural	Normal	2	Medium
	Normal	High/Induced	Normal		
	Normal	Natural	High		
C	Normal	High/Induced	High	3	High
	High	Natural	High		
	High	High/Induced	Normal		
D	High	High/Induced	High	4	Very H.

This index and the Liability Index are combined according to equation (1). The resulting Risk Index translates into a self-heating susceptibility rating factor according to:

Risk Index for Mines

Index	Rating
0 - 10	Low
10 - 20	Medium
20 - 40	High

A "Low" rating indicates a low susceptibility to self-heat and thereby initiate smoldering combustion within a coal bed or gob. A "High" rating indicates that mine operators should implement precautionary procedures to detect spontaneous combustion hot spots.

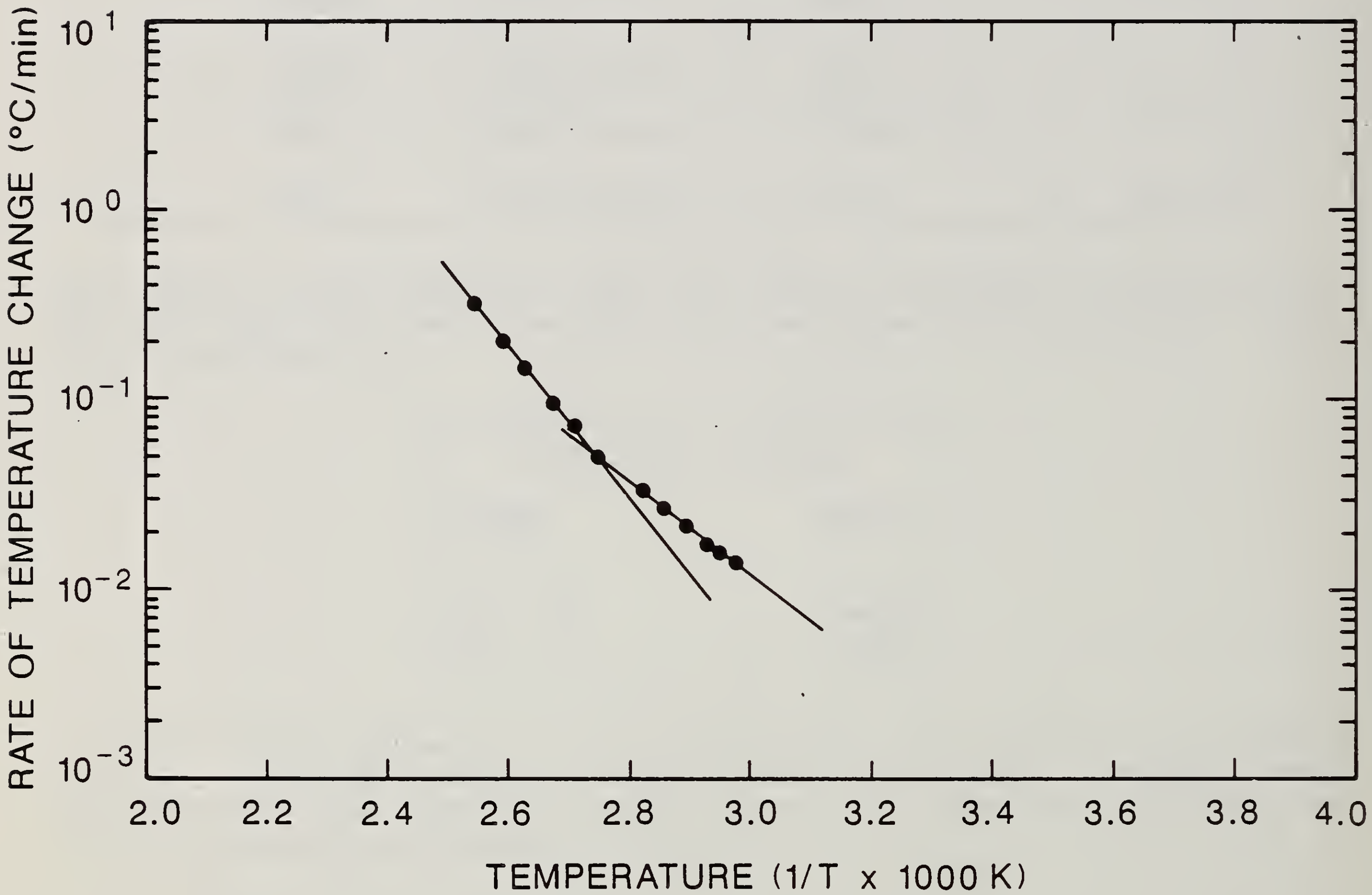
References

[1] Feng, K.K., Chakravorty, R.N., and Cochrane, T.S., Spontaneous Combustion - A Coal Mining Hazard, CIMM Bulletin, October 1973.

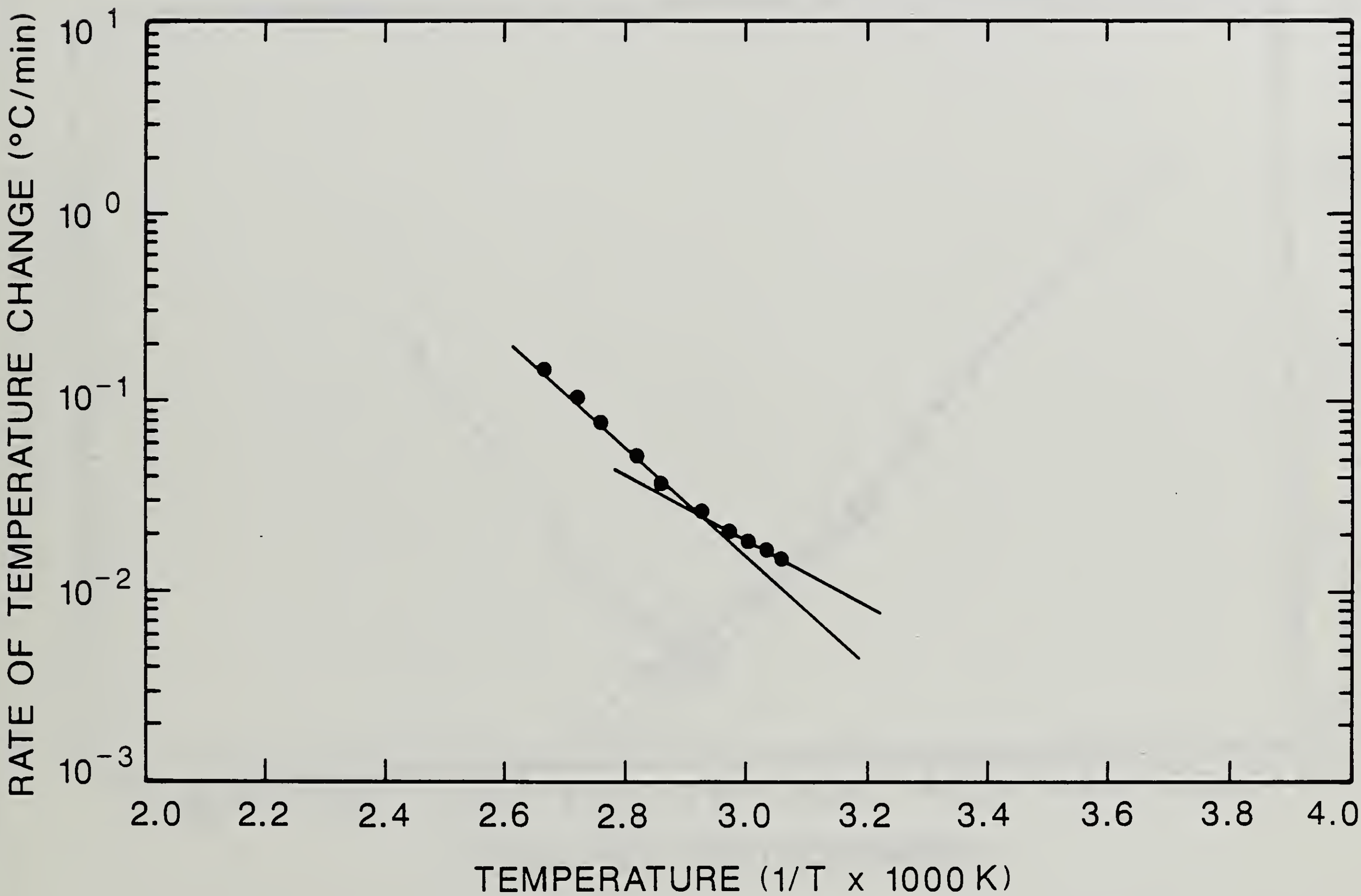
Appendix D

Adiabatic Furnace Data

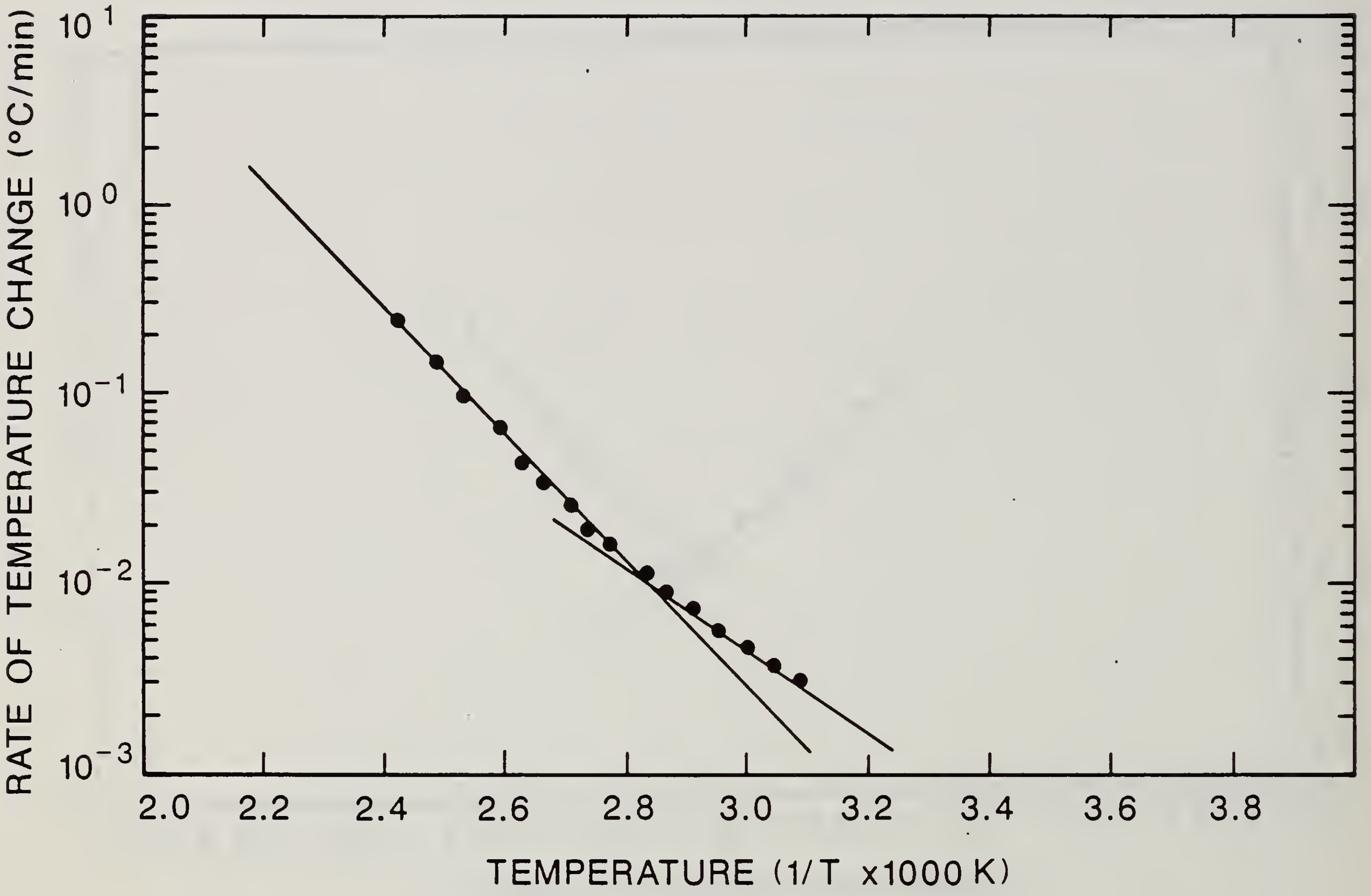
Individual Graphs



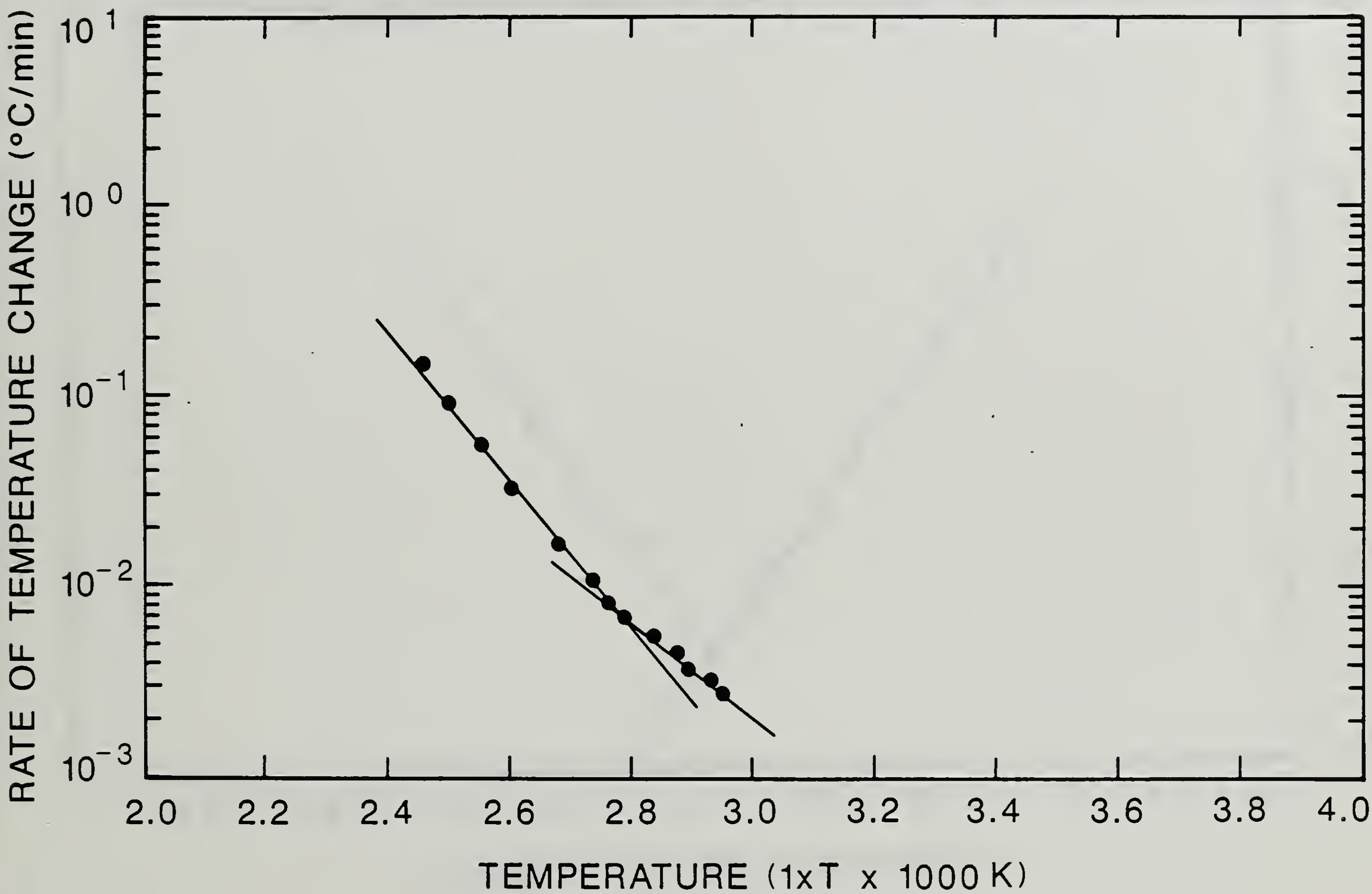
Adiabatic Furnace Test Results for the Determination
of the Reaction Rate of Coal Sample "A" in Dry Air



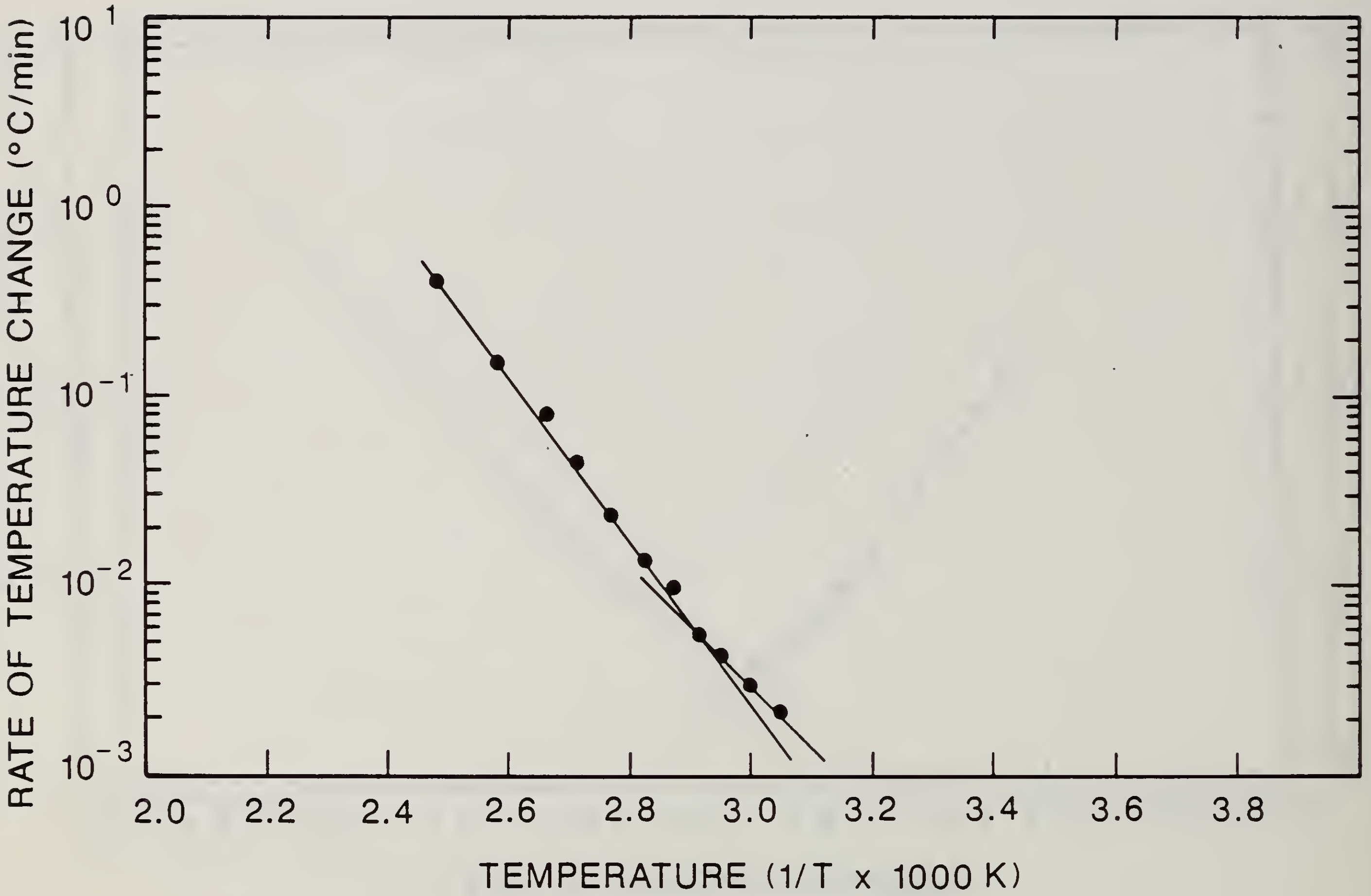
Adiabatic Furnace Test Results for the Determination of the Reaction Rate of Coal Sample "C" in Dry Air



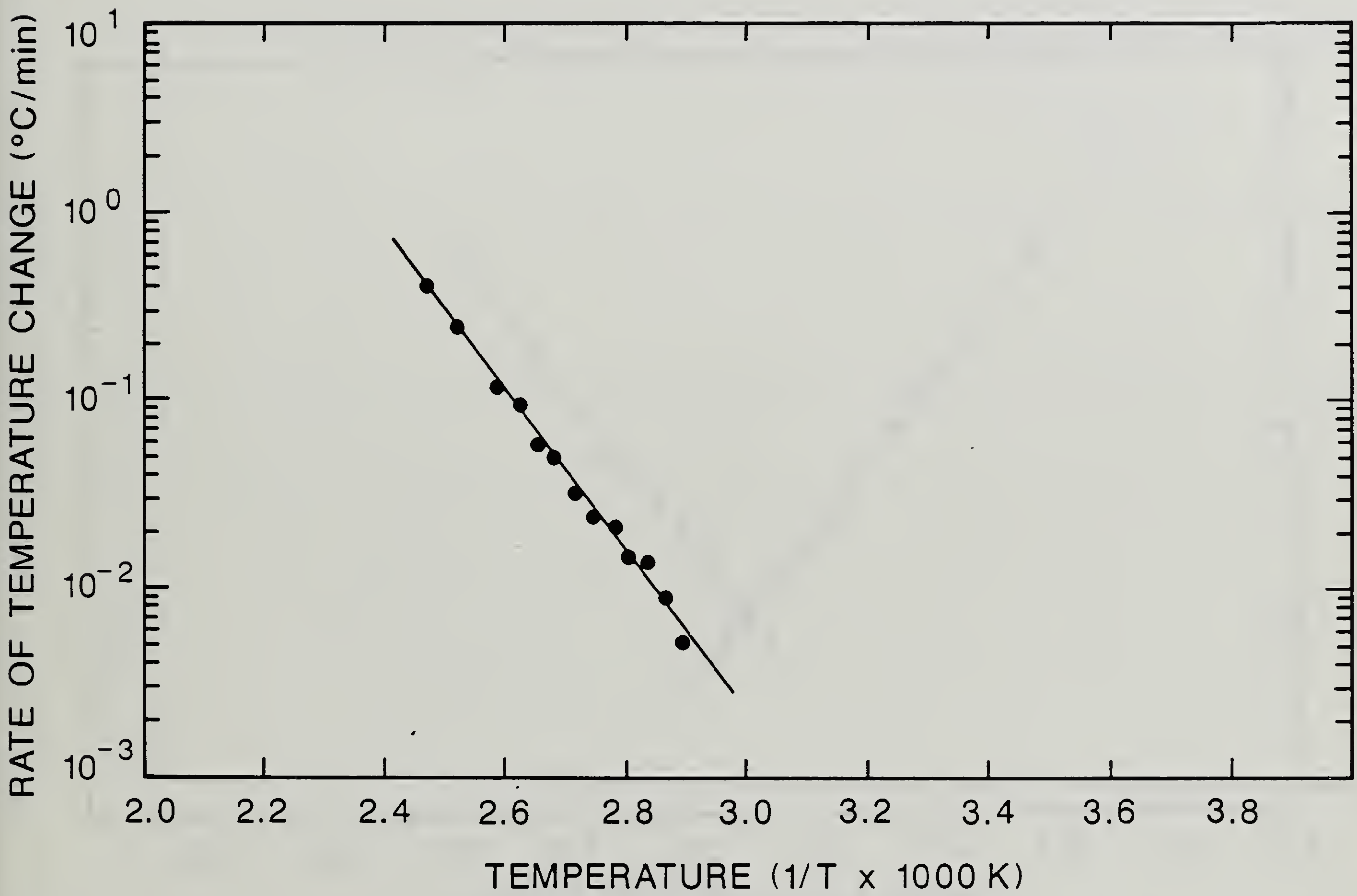
Adiabatic Furnace Test Results for the Determination of the Reaction Rate of Coal Sample "B" in Dry Air



Adiabatic Furnace Test Results for the Determination of the Reaction Rate of Coal Sample "E" in Dry Air



Adiabatic Furnace Test Results for the Determination
of the Reaction Rate of Coal Sample "D" in Dry Air



Adiabatic Furnace Test Results for the Determination
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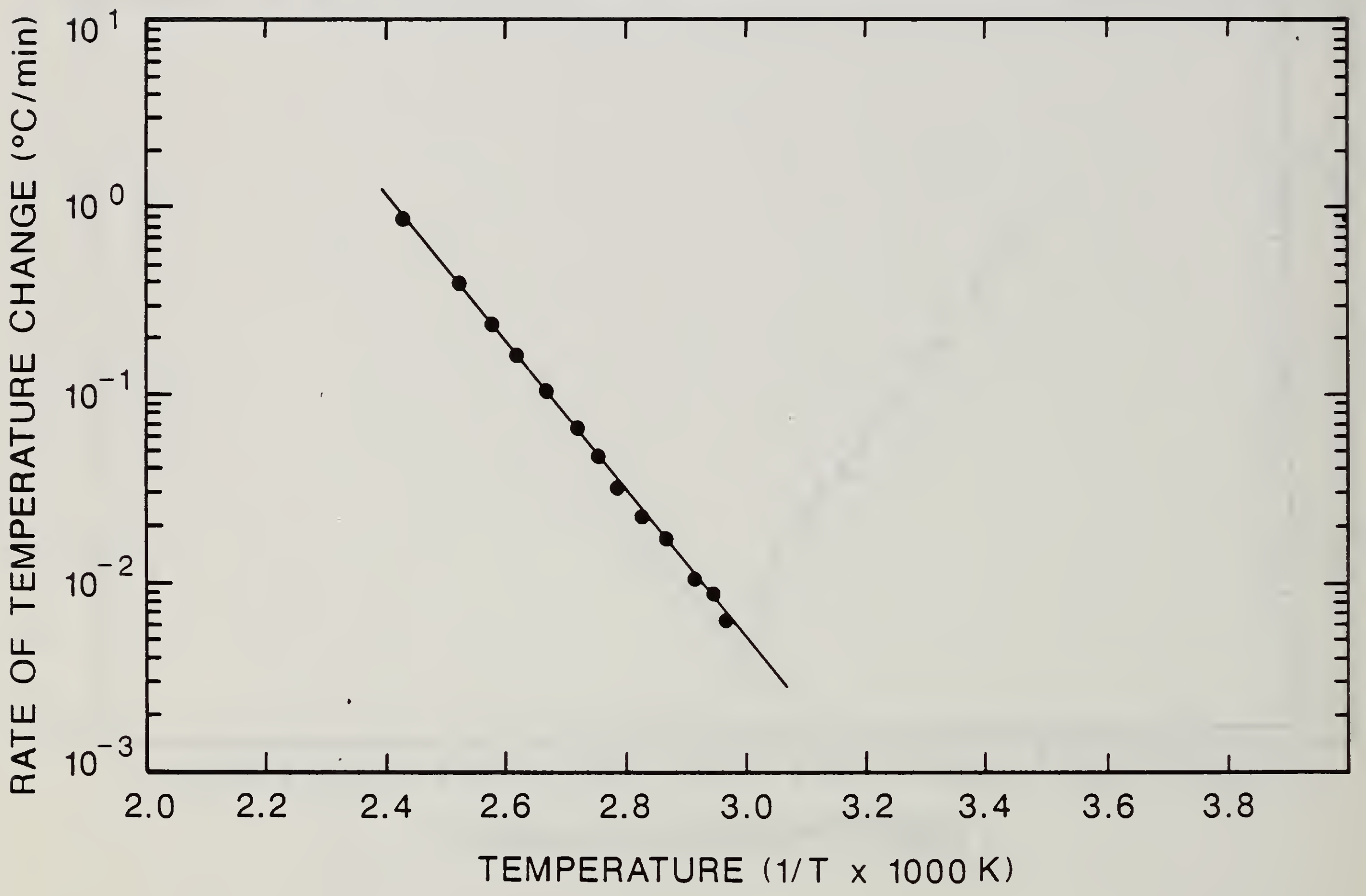
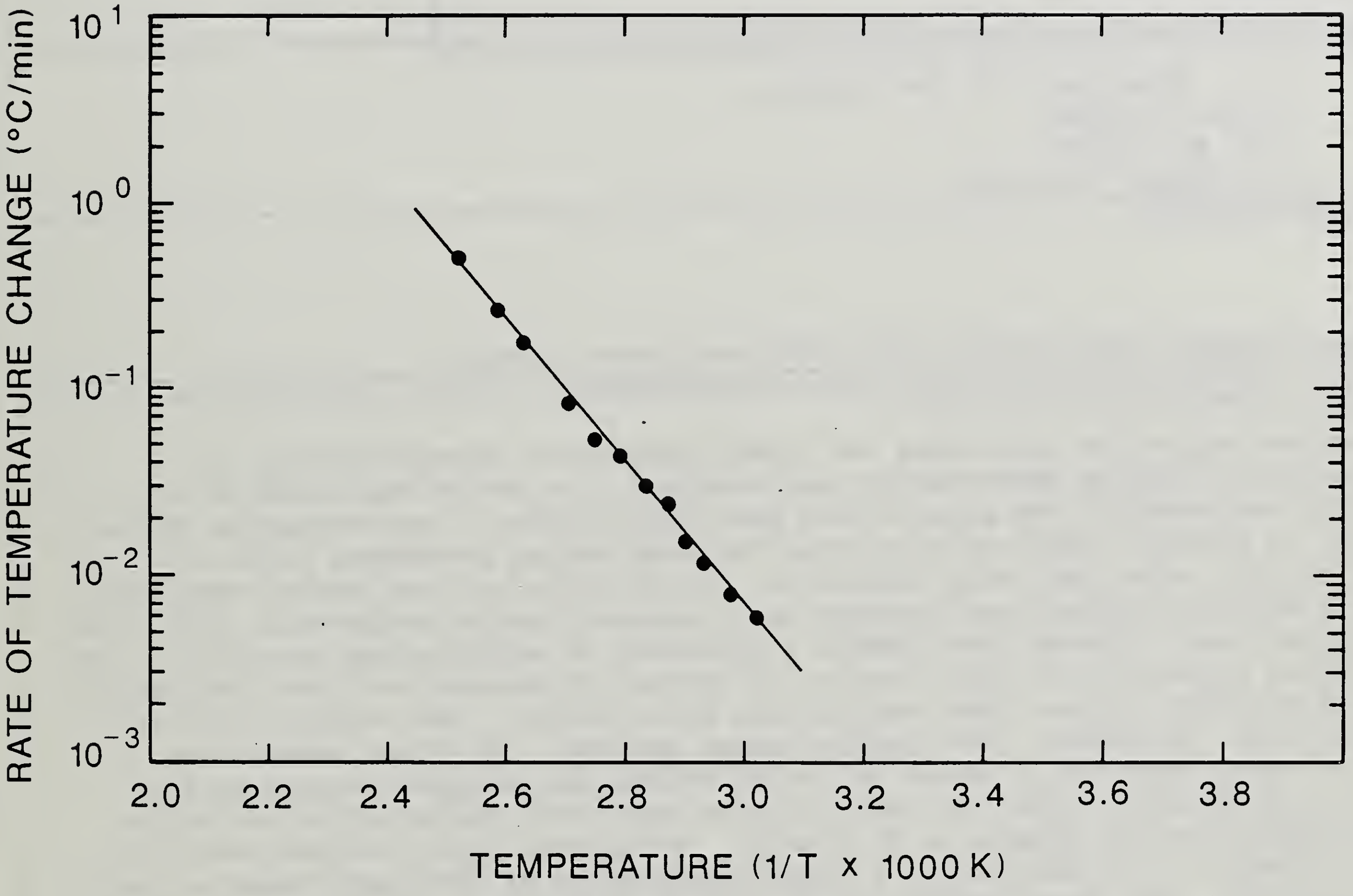


Adiabatic Furnace Test Results for the Determination of the Reaction Rate of Coal Sample "F" in Dry Air



Adiabatic Furnace Test Results for the Determination of the Reaction Rate of Coal Sample "G" in Dry Air

FORM NBS-114A (REV.11-84)

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Self Heating Properties of Coal

5. AUTHOR(S) Emil Braun

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Three methodologies for predicting the likely occurrence of self-heating in underground coal mining environments were analyzed. No method was found to be completely satisfactory for general coal mine applications. One evaluation system was found to provide excellent guidelines for preplanning procedures prior to initiating full scale coal mine operations, but it relied on past mining experience. Another evaluation system used standard coal characterization parameters, while the third system used a thermal test method a predictor of self-heating potential. The self-heating properties of eight samples of western bituminous coal were determined using the Adiabatic Furnace and the Crossing Point Method. The Adiabatic Furnace indicated that, in general, two reaction zones existed. The first temperature region extended from 25°C to about 85°C with activation energies varying from 32 kJ/mole to 55 kJ/mole, while the reaction zone above 85°C exhibited an activation energy ranging from 59 kJ/mole to 82 kJ/mole. Using this data, critical heating rates in excess of 1.5°C/24 hrs at a strata temperature of 20°C were found to result in self-heating. The Crossing Point Method yielded ignition temperatures ranging from 132°C to 154°C at an average heating rate of 0.58°C/min. An alternative plotting technique is described that suitably correlates Crossing Point Method data with end use experience. A brief review of pertinent literature is presented to provide an understanding of those factors affecting oxidative heating of coal.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Adiabatic furnace; coal; fire test methods; ignition temperature; self-heating; spontaneous combustion.

13. AVAILABILITY

☒ Unlimited

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